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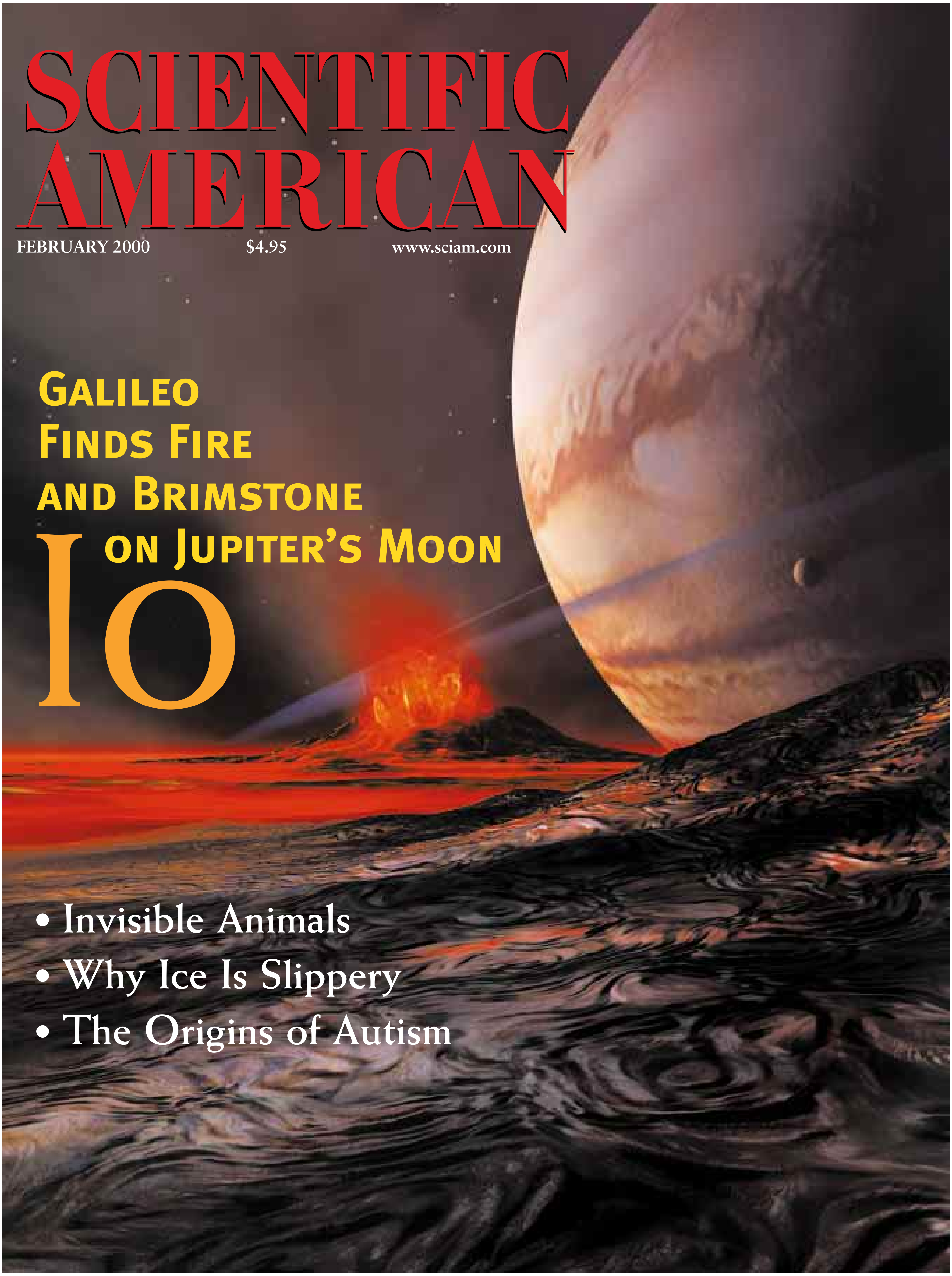

GALILEO FINDS FIRE AND BRIMSTONE ON JUPITER'S MOON IO

- Invisible Animals
- Why Ice Is Slippery
- The Origins of Autism

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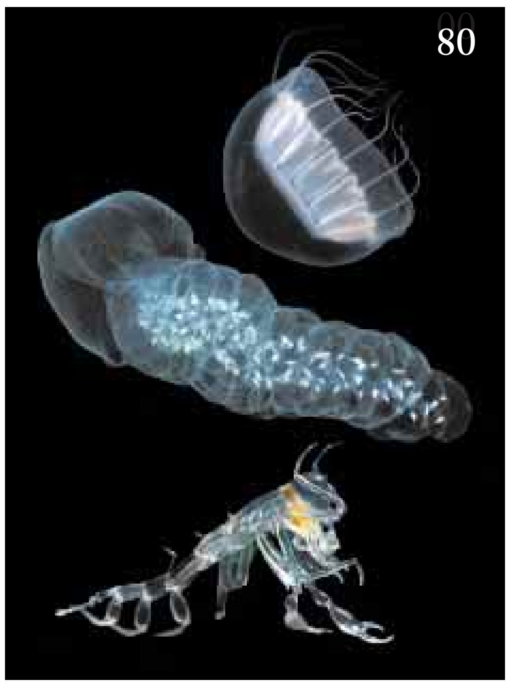

About the Cover
The volcanically active surface of Jupiter's moon Io has been studied in detail by the Galileo spacecraft. Painting by Space Channel/Philip Saunders.

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See Io's giant volcano Pele at: www.sciam.com/exhibit/1999/112999volcano

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FROM THE EDITORS

Fan Mail from the Fringe

"Let me get this straight," writes Gus Laskaris of Ruston, La. "Because Kansas no longer teaches evolution, we should call our local universities and have them refuse to admit students from Kansas? In some circles that is called blackmail." Funny, in some circles, it's called having standards.

My editorial against the Kansas Board of Education's decision to stop requiring the teaching of evolution ("Total Eclipse of Reason," October 1999) evoked hundreds of responses, bringing me untold hours of enjoyment. I've been called a Nazi brownshirt, a totalitarian, a gangster, an enemy of children, a closed-minded fanatic, an embarrassment to science, an atheist and a Democrat. (Did I miss something? Has antievolutionism really become a plank of the Republican party platform?)

What inspired this ire was my suggestion that college educators contact Kansas officials and say that, given the lowering of standards in the teaching of biology, applications from Kansan students might need to be considered more carefully. Mr. Laskaris to the contrary, I didn't say (and don't believe) that Kansas students should automatically be denied admission, if only because many good teachers will try to teach evolution anyway. But unless parents and lawmakers know that ignorance carries consequences, the quality of science education will erode.

ERICA LANSNER

Blackmailer? Fascist? Fanatic? Democrat?

The letters furious at me for attacking religion were particularly entertaining. Theirs is a telling criticism because I never mentioned religion. They correctly intuit that the hidden motive in the Kansas decision was to promote a creationist agenda by undercutting the teaching of real science—you're right, I am against that.

Some critics were offended by my calling evolution a fact instead of a theory. Evolution is the principle of modification through descent, that the traits of living populations change over time in response to differential reproductive success. It is an inescapable, mathematical result of population biology. When it happens within species, it is called microevolution. When the changes isolate parts of a population so effectively that they become different species, it is macroevolution, and that is the most reasonable explanation for what we see in the fossil record. No one yet knows precisely how evolution acted during the origin of life, but even if the first cells fell out of the blue sky, that would not erase the action of evolution since then. Evidence from every subdivision of biology and every other scientific discipline supports evolution. Evolution unifies all the diverse observations of biology as no other idea can. That is why I call it a fact.

And to the people who say they learned biology without evolution, I can only answer that chemistry and physics used to be taught without reference to atoms, but today why in heaven's name would you want to?

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

The October 1999 article "The False Crisis in Science Education," by W. Wayt Gibbs and Douglas Fox, elicited a number of letters, many of which contained additional observations and suggestions for how to better science and math education. Joseph W. Dolce, chair of the science department at Palmer Trinity School in Miami, writes, "The interpretation of the Third International Mathematics and Science Study (TIMSS) scores as a good measure of scientific knowledge rests on an important assumption—namely, that the subjects read the questions correctly. Those students who score highly on standardized tests are necessarily good readers. Sadly, but not unexpectedly, the percentage of good readers is low."

Another reader, Mark Loewe of Austin, Tex., notes, "Because American schools expect students to return their expensive textbooks at the end of each year, textbooks and teachers must repeat the same information again and again." Instead, he urges, the U.S. should "follow the lead of schools in highly achieving nations such as Sweden and Singapore and adopt science and math textbooks that students can keep. Without the redundant information, such books would be easier for children to carry and much less expensive." Additional comments concerning articles in the October issue follow.

EUROPA'S COMPLEXION

On reading "The Hidden Ocean of Europa," by Robert T. Pappalardo, James W. Head and Ronald Greeley, it occurred to me that the lack of subduction zones on Europa's surface may be owing to the icy outer shell expanding as a result of a slow, long-term cooling trend. (Such a trend may be explained by an exhaustion of radioactive isotopes or perhaps changes in its orbit.) As Europa cools, the ice crust would thicken. Because ice is less dense than water, the pressure created by the expansion of the freezing ocean would repeatedly split apart Europa's outer surface. The cooling trend would probably have been punctuated by periodic surges of heat from suboceanic volcanic eruptions. These would temporarily warm the ocean and remelt the ice from the bottom of the crust, causing it to contract. Repeated cycles of heating and cooling could account for the parallel ice ridges covering Europa's surface.

GLEN AHLERT
Fort Myers, Fla.

The authors state that a crater larger than six miles in diameter should occur every 1.5 million years, that 45 such craters have been extrapolated to exist on Europa and that this indicates an age of 30 million years. If the first two assertions are correct, the age would be 67.5 million years.

BRYAN GANGWERE
Haltom City, Tex.

Pappalardo replies:

The slow cooling that Ahlert mentions certainly could contribute to the plethora of extensional features and the lack of visible compressional features on Europa, but the answer is apparently more complex and still elusive. The problem is that expansion caused by freezing of an internal Europan ocean would produce less than a tenth of the observed increase in surface area. Perhaps compression has in fact occurred but produced subtle undulatory folds that are difficult to identify in the images. A cyclical geologic history is quite plausible. Some models predict that tectonic activity may have changed in response to orbital variations. Such changes may occur on a timescale of 100 million years, which is probably too slow to account for the formation of individual ridges but might induce periods of overall satellite activity and inactivity. Research continues to try to understand these important problems.

Gangwere correctly points out an error we made. We inadvertently reported Gene Shoemaker's estimate of the cratering rate as one crater each 1.5 million years; the prediction was actually 1.5 craters each one million years. His extrapolated number of large craters was indeed about 45, and the implied age about 30 million years. But for us to be so precise is misleading, as the error bars for both numbers were large. It is more appropriate to say that Shoemaker predicted a surface age of about 10 to 100 million years. Based on recent Galileo results, this original order-of-magnitude estimate has held up remarkably well.

ANCIENT ATOMISTS

In his article "Why Things Break," Mark E. Eberhart says, "It is only in this century that a scientific basis for understanding exactly *why* things break has surfaced" and that, similarly, scientists did not realize until "early this century that a solid is a collection of atoms held together by chemical bonds." These statements do a slight disservice to Titus Lucretius Carus, who touched on the subject repeatedly in his epic poem *De rerum natura,* written nearly 2,000 years ago. Lucretius, in turn, drew on the work of his predecessors, Epicurus, Leucippus and Democritus. Scientific proof (and disproof) of their philosophies was centuries away, but their ancient contribution should not be downplayed.

GEOFF MARSHALL
Toronto, Ontario

Eberhart replies:

It has always fascinated me that the ancients developed the concept of atoms. Indeed, by the 14th and 15th centuries the notion had become fairly sophisticated, and the idea of a material made by the packing of spheres was used to explain the cleavage patterns observed when cutting precious stones. (These ideas were lost and did not resurface until the 20th century.) I was, however, careful to say that a *scientific* basis for why things break emerged in the 20th century. Although science is poetry, poetry is not science, and merely believing in atoms does not provide a means to change the way in which something breaks.

TRUTHFUL TELLER?

Regarding the profile of Edward Teller by Gary Stix [News and Analysis], as a member of the Los Alamos National Laboratory effort to develop the first U.S. hydrogen bombs, I am troubled by Teller's assertion that Stanislaw Ulam did not contribute to the cause. Unlike Teller, Ulam was a very modest person and never needed attention. His colleagues knew of his contributions to physics and mathematics and to the development of our nation's nuclear stockpile. For Teller to state that Ulam didn't contribute is utter nonsense.

HAROLD M. AGNEW
Director, Los Alamos
Scientific Laboratory, 1970–1979
via e-mail

Letters to the editors should be sent by e-mail to editors@sciam.com or by post to Scientific American, 415 Madison Ave., New York, NY 10017.

ERRATUM

In "Vision: A Window on Consciousness," by Nikos K. Logothetis [November 1999], the diagram of the human brain's visual cortex on page 72 contains some misleading statements. The function of V4v is not unknown: V4 is believed to be essential for perceiving color and perhaps form. The existence and positions of areas V7 and V8 are controversial among scientists, and Logothetis rejects the pictured assignments. Through an editing oversight, he was not given a chance to correct the art before it went to press.

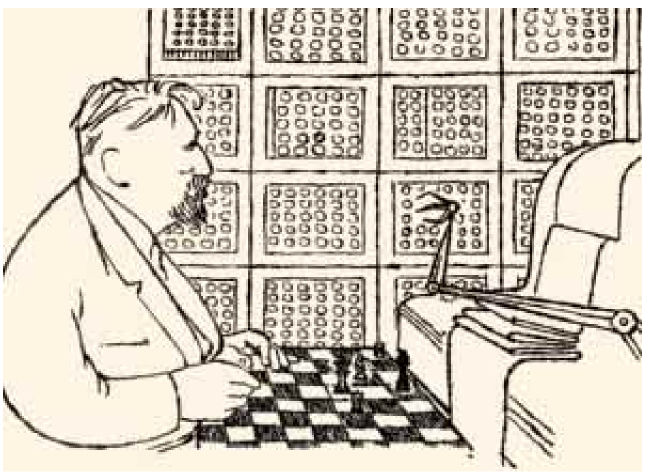
50, 100 AND 150 YEARS AGO

SCIENTIFIC AMERICAN

FEBRUARY 1950

THE TORRID LYSENKO CONTROVERSY—"Among U.S. geneticists, Tracy M. Sonneborn is the one whose work seemingly comes closest to supporting the theory of inheritance of acquired characteristics championed by the Soviet biologist Trofim D. Lysenko. Sonneborn has shown that there are two types of single-celled paramecia and that one can be transformed into the other by environmental factors, such as heat or limiting the supply of food. The transformation is hereditary, though it is passed along from generation to generation not by genes in the nucleus of the cell but by 'plasmagenes' in the cytoplasm surrounding the nucleus. Sonneborn, however, declared that Lysenkoists who have seized upon his results as confirmation of their position have misinterpreted them."

CHESS-PLAYING COMPUTERS—"Could a machine be designed that would be capable of 'thinking'? Some of the possibilities can be illustrated by setting up a computer in such a way that it will play a fair game of chess (*below*). Under some circumstances the machine might well defeat the program designer. Sufficiently nettled, however, the designer could easily weaken the playing skill of the machine by changing the program. The chief weakness of the machine is that it will not learn by its mistakes. —Claude E. Shannon" [*Editors' note: Shannon is considered to be the founder of the academic field of information theory.*]



A computer that plays chess

FEBRUARY 1900

FIRST NOBEL PRIZES—"Candidates for the Nobel prize for scientific achievements are now being considered by the Swedish Academy of Science, at Stockholm, which must award the prize this year for the first time. Among the names already proposed are Prof. Roentgen, Marconi, Baron Nordenskjöld, and Henri Dunant, the founder of the Red Cross Society." [*Editors' note: Wilhelm Roentgen and Dunant won in 1901, and Guglielmo Marconi in 1909. Nordenskjöld died in 1901.*]

MECHANICAL RICE PICKER—"In 1898 the United States produced less than half the amount of rice we consume. Rice, in addition to its subtropical character, is a crop growing chiefly on wet lands, where it has hitherto been impossible to use harvesting machinery. It must, therefore, be laboriously cut by hand with a sickle. In 1884, enterprising settlers in Louisiana began the development of a new system of rice culture. As now perfected, the dry prairie lands are flooded by a system of pumps, canal, and levees, and when the rice is about to mature the water is drained off, leaving the land dry enough for the use of reaping machines. Under this system the industry has undergone a rapid development."

QUICKER, CHEAPER—"The United States Bureau of Labor has been investigating the effect of displacement of hand labor by machinery in the iron and steel trade. It was found that in 1857 a rifle barrel took 98 hours to make by hand. It is now made in 3 hours and 40 minutes."

CURE FOR MORAL TURPITUDE—"Dr. John D. Quackenbos, of Columbia University, has long been engaged in experiments in using hypnotic suggestion for the correction of moral infirmities and defects such as kleptomania, the drink habit, and in children habits of lying and petty thieving. Dr. Quackenbos says, 'I find out all I can about the extent of a patient's weakness. For each patient I have to find some ambition, some strong conscious tendency to appeal to, and then my suggestion, as an unconscious impulse, controls the moral weakness by inducing the patient to further his desires by honest means. Of course, if a man has, like one of my patients, no ambition in the world save to be a good billiard-player, he can't be cured of the liquor habit, because his highest ambition takes him straight into danger.' "

FEBRUARY 1850

GOITER—"M. Grange read a paper before the Paris Academy of Sciences on that terrible disease in the Swiss valleys, named the Goitre. He stated that the cause of it was magnesia in the waters, and that it could be cured by administering minute doses of iodine salts."

AGASSIZ ON INSECTS—"In a recent lecture, the celebrated Professor Agassiz said more than a lifetime would be necessary to enumerate and describe the various species of insects. There are numerous species collected in the museums of Europe, but even of these, the habits and metamorphoses are almost entirely unknown. Meiger, a German, who devoted his whole life to the study, had collected and described six thousand species of flies, which he collected in a district ten miles in circumference, but of their habits he knew scarcely any thing."

WARM RECEPTION— "The whale which made a pleasure excursion into Provincetown harbor last week was very inhospitably treated by the people of that place, being harpooned and cut up within an hour after his arrival. He made about fifty barrels of oil."

NEWS AND ANALYSIS

IN FOCUS

NASA'S NOT SHINING MOMENTS

The space agency's approach, including its "faster, better, cheaper" credo, may be a recipe for disaster

DAMIAN DOVARGANES *AP Photo/POOL*

***NOT PHONING HOME:** Mission controllers anxiously waited for a signal from the Mars Polar Lander in early December, which sadly never came.*

Spaceflight remains such an expensive, hazardous, edge-of-the-precipice activity that the cost of disasters can be staggering. The presumed loss of the Mars Polar Lander in December 1999 is only the latest setback. The Mars Climate Orbiter spacecraft crashed into the destination planet's atmosphere and was destroyed last September 23 because of navigation judgment errors. The entire space shuttle fleet was grounded for nearly half a year when a short circuit from a mishandled wire bundle nearly led to an emergency landing in July; more than 100 similarly frayed wires were subsequently found in other shuttles.

The recent blizzard of U.S. space accidents traceable to sloppiness applies not only to the National Aeronautics and Space Administration but also to its aerospace contractors, such as Lockheed Martin and Boeing. The total costs far exceed $3 billion, out of an annual national space budget of about $30 billion. Errors can never be totally eliminated—this is rocket science, after all. But many observers have been alarmed at the apparent increase, which could be a symptom of deeper problems that could lead to more failures in the future. Observers and old-time NASA personnel fear that the agency's current philosophies, including its "faster, better, cheaper" credo—the use of more frequent but smaller-scale, less expensive missions—may not be leaving enough room for quality control.

Launches are the most common point of failure and markedly illustrate the kind of mistakes critics say are avoidable. Two potentially serious problems occurred on the STS-93 shuttle flight in July, which launched the Chandra X-ray Observatory. The first, at main engine ignition, saw an improperly fastened pin fall from inside one of the rocket engines, piercing the thin piping that circulates the cryogenic hydrogen fuel through a nozzle to cool the structure. The resulting loss of fuel, though small, caused the shuttle engines to shut down prematurely, just short of the craft's planned altitude. The second problem involved a short circuit several seconds into the flight, which took two computers that control the main engines off line, forcing backup systems to complete the ascent.

Engineers traced the short circuit to worn insulation on cables running the length of the shuttle's payload bay. The source of the wear was not clear, so NASA prudently examined all of the shuttle fleet's wiring. More than 100 additional cases of wear, including some as serious as the one that nearly aborted STS-93, were found and repaired. NASA determined the cause to have been careless handling and bumping by workers.

A string of handling errors continued even as NASA struggled to recover from the frayed-wire near miss. Workers ran a test on a wing elevon (a combined elevator and aileron) without removing a support structure, and as a result several spars harpooned the elevon, requiring its replacement. One main engine had to be replaced when x-rays discovered that a drill bit had been left inside engine plumbing. (Such sloppiness is not limited to NASA systems: the European Space Agency's first launch of the Ariane 5 heavy booster blew up in 1996 because of a software oversight, and its SOHO satellite went out of control in mid-1998, apparently because overworked technicians failed to monitor it properly. Commercial rockets in the U.S. and Russia also suffered a rash of launch explosions in 1998 and 1999.)

PIERRE DuCHARME *Reuters/Archive Photos*

FAILURE OF TITAN IV ROCKETS was traced to shortcuts in quality control.

In September an independent review of a string of expensive failures by Lockheed Martin's Titan IV rockets concluded that "the company focused too heavily on cutting costs and not enough on supervising the quality of its work," according to press accounts. Henry Spencer, a regular commentator on space events, provided more details in a privately circulated report. In addition to the emphasis on cost cutting, he reported that the study found "lack of accountability and well-defined responsibility, growing problems with skills retention, violations of traditionally rigorous rules about testing flight hardware, procedures overly vulnerable to human error, declining workforce quality, and poor customer communications."

Edward M. Hanna, a management consultant for the aerospace safety group FasterBetterCheaper.com, stated in an article circulated around NASA last summer that "there's been a tendency to replace older, more experienced workers with younger people. And that's related to a loss of quality." After a five-year study into the declining quality of aerospace work, Hanna's group determined that "cost cutting and short-term objectives have taken priority over the retention of an experienced core of talent." As a result, wages in aerospace are 20 percent below those of other engineering professions, when the criticality of quality requirements should demand not parity but 20 to 50 percent higher salaries, according to Hanna.

Besides the retention problem ("erosion of critical skills" is the phrase most commonly used within NASA), there are other roadblocks to quality work. For example, the technology itself is more complex and unforgiving. Norman Augustine, former chief executive of Lockheed Martin and a frequent commentator on aerospace quality techniques, told the *Washington Post* that "after the fact, it's always obvious what went wrong. But before the fact, the problems are so hard to find."

Another obstacle is the style of some managers. The key to success, Augustine says, is a culture where workers know "they won't lose their heads" if they tell the boss bad news. His rule: "We'll tolerate problems, but we won't tolerate not reporting them." NASA had this kind of leadership in the 1960s, when men such as Robert R. Gilruth led the successful Apollo program. But agency insiders privately describe how such an approach sadly never caught on at some other centers and is alien to the style of current leadership at NASA, which has been run since 1992 by Daniel S. Goldin.

"The organization that I spent most of my professional career in had these same problems," states Charles Harlan, the now retired head of safety at the NASA Johnson Space Center in Houston. "The current top management at NASA is famous for 'kill the messenger'–type management style." Harlan, now an aerospace safety consultant, concludes: "It is somewhat depressing that neither Boeing nor NASA can rise above this kind of behavior."

Early in December a presidential board on space launch accidents released its report. The main causes of the incidents were connected with engineering and fabrication flaws when the boosters were being assembled, resulting from a lack of adequate management attention and also possibly from the loss of the most experienced employees to retirement and layoffs. "Maintaining management, technical and engineering oversight expertise is becoming increasingly difficult in both government and industry," the report stated.

Last year's space setbacks are certain to create a psychological rebound, in which workers try harder to avoid future disasters. NASA has publicly stated that its approach is still fundamentally sound, although it admits that its Mars strategy needs major rethinking in the wake of the Mars Polar Lander and Climate Orbiter disappearances. The agency may postpone the next landing attempt, scheduled for 2001, as it tries to determine whether the Mars program is sufficiently well designed and budgeted. But in the long run, NASA will have to address its systemic weaknesses if it is to avoid a new string of expensive, embarrassing and perhaps in some cases life-threatening foul-ups. *—James Oberg*

JAMES OBERG (www.jamesoberg.com) is a 22-year veteran of space shuttle operations and now an independent consultant and writer based in Dickinson, Tex.

CHEMISTRY

AN ELEMENTAL MYSTERY

Who really *discovered element 43?*

In 1925 German chemist Ida Tacke and her colleagues made a stunning announcement. Using x-ray spectroscopy, they had reportedly discovered element 43, which they dubbed masurium. For various reasons, however, their work gained little acceptance. Ernest O. Lawrence, the Nobel Prize–winning physicist, called the masurium investigators "apparently deluded." In 1937 credit for the discovery of element 43 went to Carlo Perrier and Emilio Segrè, who christened the substance technetium. But recent research has bolstered the masurium claim, inviting a close reexamination of the evidence.

In their work, Tacke, Walter Noddack (who would become her husband) and Otto Berg fired a beam of electrons at different materials, inducing them to emit x-rays. It was widely known at the time that the wavelengths of the x-rays were directly related to the atomic numbers of the elements in the bombarded substance. With this technique, the Noddack team analyzed columbite ores—a black mineral consisting of niobium—and obtained faint x-ray spectral lines that appeared to correspond to the radioactive element 43.

But scientists discounted the work, assuming that the relatively short half-life of element 43 (210,000 years for one of its isotopes) would preclude its natural existence on the earth. (The technetium that Perrier and Segrè had discovered was created artificially in a cyclotron, by smashing subatomic particles into element 42, molybdenum.) Also, the fact that Tacke, who died more than 20 years ago, was a female chemist—not a physicist—without a major faculty position probably did not aid her cause.

But scientists have since learned that technetium can indeed occur naturally from the spontaneous fission of uranium. Recently David Curtis of Los Alamos National Laboratory and his colleagues detected technetium in uranium ores from a Canadian deposit, confirming earlier research from the 1960s. The amount, though, was minuscule—only billionths of a gram of technetium for every kilogram of uranium. Nevertheless, the ores studied by the Noddacks and Berg may have contained as much as 10 percent uranium, prompting the question of whether their experimental apparatus had the sensitivity to detect such minute traces.

AIP EMILIO SEGRÈ VISUAL ARCHIVES, GIFT OF JOST LEMMERICH

IDA TACKE said she had co-discovered element 43 in 1925, but her claim was widely ridiculed. New research suggests the German chemist could have been right.

To answer that, chemist John T. Armstrong of the National Institute of Standards and Technology used spectral-analyzer software and a database containing high-precision x-ray measurements to simulate the work of the Noddack team. By essentially running a series of virtual experiments, Armstrong found that the masurium data are indeed consistent with the presence of element 43 in the columbite ores. Furthermore, his results indicate that the instruments used by the Noddacks and Berg could have had the necessary sensitivity to detect less than a billionth of a gram of element 43 in a tiny amount of residue extracted from the chemical separation of a kilogram of ore. "After all this analysis," Armstrong concludes, "I think it's highly likely that they did discover element 43."

Other factors are provocative. Using the same technique of x-ray spectroscopy, the Noddacks and Berg did rightly discover element 75, which they named rhenium. In fact, they reported that data in the same paper in which they described their masurium work. And Tacke was the first to propose that nuclear fission might account for some of Enrico Fermi's experimental results in which the noted physicist thought he had synthesized transuranic elements. Tacke turned out to be right and Fermi wrong. (Interestingly, Fermi won a Nobel Prize for his supposed discovery of the transuranic elements.)

Still, the masurium claim is far from assured. The Noddacks and Berg made a horrific error in their 1925 paper by reporting to have detected an amount of element 43 that was impossibly high by *several* orders of magnitude. And because they did not publish extensive details of their experiments, simulating the labwork required Armstrong and Pieter Van Assche of Katholieke Universiteit Leuven in Belgium to deduce some of the instrumental and analytical conditions. Among their favorable assumptions is that a magnetic focusing technique was used to target the beam of electrons to an area less than one square millimeter.

Nevertheless, the case for the Noddacks and Berg, while hardly conclusive, has never been stronger. "Originally, I thought it was impossible that they had discovered technetium. But after looking more closely into it, I decided that you couldn't automatically throw out their claim," says Albert Ghiorso of Lawrence Berkeley National Laboratory. Ghiorso, by the way, worked with Glenn T. Seaborg to discover several of the transuranic elements that had eluded Fermi.

—Alden M. Hayashi

PHYSICS

THE NONNEGLIGIBLE LIGHTNESS OF GRAVITY

Physicists verify that even gravity itself has weight

Planet Earth is about three trillion tons lighter than the sum of its parts. But never fear, the ground beneath your feet is not draining away into a cosmic sinkhole. No, what sounds at first like an accounting error of global proportions is just the gravitational binding energy of Earth—the effect of Earth's gravity acting on Earth's six billion trillion tons. Like all binding energies, this small self-energy is a negative quantity. And, as Albert Einstein told us, energy is mass, in this case, three trillion tons' worth subtracted away by the force of gravity.

But what kind of mass? There is inertial mass, which makes it hard to push a stalled car along a level road, and there is gravitational mass, which a mechanic's hydraulic jack contends with when holding the car up for repairs. In most situations, these two masses should be identical, an idea that is enshrined in the equivalence principle: everything is accelerated the same amount by the same gravitational field. Now an experiment carried out by Eric Adelberger, Blayne Heckel, Stefan Baessler and coworkers at the University of Washington has confirmed that even the ethereal gravitational self-energy obeys the equivalence principle.

The equivalence principle lies at the heart of physicists' theories of gravity. Galileo demonstrated it about 400 years ago, so the story goes, by dropping balls off the Leaning Tower of Pisa and observing that large and small balls fell at the same rate. Einstein used it as a guiding principle that led him to his general theory of relativity, which describes gravity as a warping of space and time.

Yet there are reasons to look for violations of the equivalence principle: a quantum theory of gravity would almost certainly introduce small new effects that would spoil exact adherence to the principle. Violations could also have implications for neutrino oscillations, the amount of dark matter in the universe and the expansion of the universe.

Laboratory experiments have verified the equivalence principle for small objects made of different materials, such as aluminum and platinum. None of those experiments, however, say anything about gravitational self-energy, because lab objects have negligible self-energies.

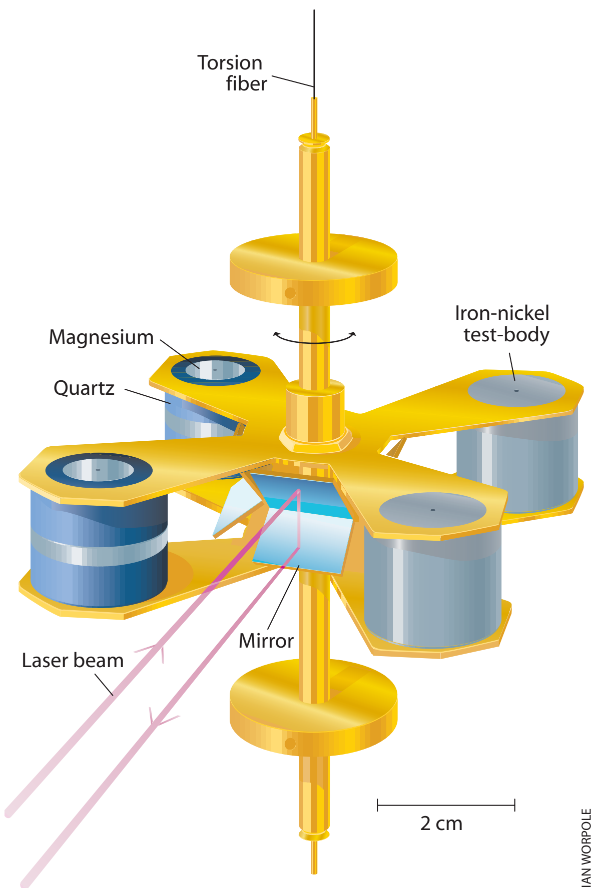
Fortunately, Nature has supplied a couple of test masses with small but sufficient self-energies and placed them in a gravitational field: Earth and the moon in the field of the sun. Nature neglected to assemble all the equipment for the experiment, but Apollo astronauts corrected this oversight by placing mirrors on the moon to reflect laser beams back to Earth. By studying the changing distance between Earth and the moon to an accuracy of one centimeter, scientists have verified that both these test masses accelerate toward the sun at the same rate, to an accuracy of one part in two trillion, implying that their minuscule self-energies obey the equivalence principle to about one part in 1,000.

Nevertheless, a coincidence could have been fooling researchers. The compositions of Earth and the moon are different. Earth has a much higher proportion of iron and nickel because of its sizable core, whereas the moon has more silicon and magnesium, rather like Earth's mantle. So what if a violation of the equivalence principle caused by those compositional differences happened to cancel out an opposite violation caused by the different self-energies?

The Seattle experiment rules out that possibility. The researchers placed test masses of steel (mostly iron and nickel) and of magnesium and quartz (silicon dioxide) on a pendulum suspended on a fine tungsten wire inside a vacuum chamber. If the masses, roughly mimicking the compositions of Earth's core and the moon, are pulled toward the sun by different amounts, the discrepancy will show up in the twisting oscillations of the pendulum, which are monitored by lasers reflecting off mirrors.

Exquisite precision and elimination of sources of error are required. For example, the lab tilts slightly during working hours when cars fill a nearby parking lot. The varying gravitational force from moisture in a nearby hillside and the magnetic field of the solar wind also have measurable effects. Despite these difficulties, data recorded across a 10-month span have verified the equivalence principle for the ersatz moon and Earth to slightly better accuracy than the lunar laser-ranging experiments. Combining the two results provides the best verification to date that the equivalence principle applies to gravitational self-energy and that the self-energy has "weight" like any other mass, albeit in the negative sense of reducing an object's weight.

The group is working on further improving the experiment's accuracy, as well as experiments to look for deviations in gravity caused by small, extra space dimensions predicted by some particle theories. *—Graham P. Collins*



***GOLD-PLATED TORSION PENDULUM** is used to test the equivalence principle. If the sun's gravity pulls unequally on the cylinders, the pendulum rotates, deflecting the laser beam.*

IN BRIEF

Genetic Landmark

Scientists associated with the Human Genome Project have deciphered the genetic code of chromosome 22, the second smallest in the human set of 23 pairs. The team read small overlapping units of DNA and then pieced them together like a jigsaw puzzle to produce the 33.4-million-base-pair sequence. The report, in the December 2, 1999, *Nature,* also identified 11 gaps—short stretches of repetitious code—that were not readable with current techniques. Researchers found evidence for at least 545 genes, and except for a few known to play a role in diseases such as leukemia and schizophrenia, most were unfamiliar. *—Diane Martindale*

Faulty Idea?

The rubbing slabs that form the San Andreas Fault seem to produce less heat than other faults do, suggesting that the San Andreas is lubricated somehow and is hence unique. At last December's meeting of the American Geophysical Union, Chris Scholz of Columbia University's Lamont-Doherty Earth Observatory argued that the prevailing view is wrong: the fault is actually typical, based on a review of existing data and current understanding of rock friction. An unseen fluid, Scholz says, may be removing the missing heat through convection. If he is correct, certain geologic phenomena may exist that could lead to better earthquake predictions on the fault. *—Philip Yam*

TOM BEAN *Corbis*

Cool fault

Cell-Phone Forgettable

Although experts doubt that the microwave energy from cell phones causes brain tumors, they note that questions still remain about other possible effects from the phones. Henry Lai of the University of Washington reports in the January *Bioelectromagnetics* that cell phone–type microwaves affect learning and memory in rats. Those exposed for an hour to the pulsed microwaves were slower to learn the location of a platform in a water maze than unexposed rats were. Moreover, they seemed to lose their memory of the location of the underwater platform on later tests. *—P.Y.*

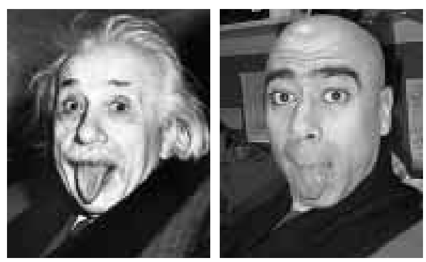
More "In Brief" on page 24

ANTI GRAVITY

Worth a Thousand Words

Millennial fever seems to be finally breaking, which allows one important, unresolved question to assume prominence in our collective consideration: How do you throw away a garbage can? I keep trying; the sanitation guys keep leaving it. If you refuse to ruminate on this refuse rubbish, here are a few other questions to distract you from the garbage can koan.

The following true/false queries refer to photographs in this magazine in 1999. Although serious subscribers will probably derive the most satisfaction from this second annual February quiz, casual readers should still be entertained. And if you borrowed the issue from your dentist's office as part of an effort to appear erudite, just remember to call it Scientific *American,* not *America*. "Oh, I've been reading *Scientific America* for years" is probably the second most common thing a member of the staff hears, the first being, "Jeez, I would have thought a magazine editor could afford a nicer apartment." Anyway, here's the quiz.



Who appeared in Scientific American *more in 1999, Einstein or Zorpette?*

1. This magazine ran a photo of a relative of a Nobel laureate in chemistry apparently piloting some kind of flying vehicle.

True, sort of. Captain Jean-Luc Picard of the Federation Starship *Enterprise* appears on page 42 of the January issue. The fictional Captain Picard has made reference to his fictional relative who won the chemistry Nobel.

2. We featured a picture of the young Albert Einstein, in his annus mirabilus of 1905, standing behind a podium.

False. In the photograph, on page 16 of the March issue, the young Einstein is standing behind a lectern. Often incorrectly referred to as a podium, a *lectern* is that thing you stand behind, and put your notes and elbows on, when delivering a *lecture*. A *podium* is the thing you stand on, after which you might visit a *podiatrist*. Over the year, three different Einstein photos were published, the other two appearing on page 81 of June and on page 26 of September.

3. Four different photos of intrepid *Scientific American* reporter Glenn Zorpette appeared in various issues in 1999.

False. Zorpette was indeed pictured on page 4 of the June issue, standing on a bat-hunting lobster boat; on page 20 of the August issue, being bled on board a bike; and on page 26 of the November issue, floating weightless within the "Vomit Comet" aircraft. But the ad photo on page 5 of the June issue is of an individual he merely resembles. Zorpette thus ties Einstein for 1999 appearances. Einstein is still way ahead overall, and he and Zorpette are easily distinguishable since the latter began shaving his head. Telling Zorpette, especially when weightless, apart from Jean-Luc Picard is more problematic.

4. The December issue features photos of two famous scientists whose first name is Francis.

True. Francis Crick, co-discoverer of the structure of DNA, is on page 65, and Francis S. Collins, director of the National Institutes of Health's National Human Genome Research Institute, is on page 91. But Francis Bacon, often credited with developing the scientific method, is not pictured. Had he been born in Paris, rather than across the Channel, he would have been France's Bacon.

5. The December issue put to rest the signature question regarding the lack of realization of the technological dreams of the 1960s, namely, where are the flying cars already?

True. Asked by Jerry and George on *Seinfeld,* and more recently by Gail Collins in the *New York Times,* "Where are the flying cars already?" was addressed on page 50, with the photo of Moller International's M400 Skycar. The vehicle carries a price tag of $1 million for now, putting it well out of the price range of the average scientific American. So the answer to "Where are the flying cars already?" is, "It's not enough that you have a computer in your house more powerful than anything that navigated a manned moon landing, you still want to fly around the neighborhood like Glenn Zorpette, I mean, like Jean-Luc Picard?"

—Steve Mirsky

BETTMANN/CORBIS (*Einstein*); STEVE MIRSKY (*Zorpette*)

In Brief, *continued from page 22*

Life from Scratch

Geneticists have determined the minimum number of genes for life. Writing in the December 10, 1999, *Science,* the researchers looked at the two smallest bacteria known (called mycoplasma), which have about 500 genes, and found that at least 265 to 350 are necessary. The study provides clues to the nature of life and may pave the way for simple life-forms to be custom-made in the lab, although that step, requiring lipids, sugars and other cellular components, is still a ways off. An accompanying article by bioethicists finds no moral quandaries now but observes that questions will continually arise as technology improves. —P.Y.

Minty Insecticide

Move over, citronella: scientists led by Padma Vesudevan of the Indian Institute of Technology in New Delhi have determined that peppermint oil can also repel mosquitoes and kill the larvae. They floated films of the oil, extracted from the peppermint plant *Mentha piperita,* on top of larvae-filled water; a day later nearly all the larvae were killed. The protection rate, based on the experience of volunteers who spent several nights outside, averaged 85 percent. The oil was especially effective against *Anopheles culicifacies,* the principal carrier of malaria in India. The work is to appear in an upcoming issue of *Bioresource Technology*. —D.M.

Swatted

TONY BRAIN *SPL/Photo Researchers, Inc.*

Speed Demons

Your 56K modem is toast in the future: on the next-generation Internet, researchers transmitted standard Internet protocol data 40,000 times faster, at 2.4 gigabits per second. The record feat, done last November by a consortium that includes the University of Washington and Microsoft, transmitted the equivalent of 150 cable television channels. Researchers at Lucent Technologies's Bell Labs also announced data transmission records, but through optical fibers. They crammed 1,022 wavelengths of light into a single fiber (commercial systems carry about 100, and each wavelength is a channel); system capacity was 37 gigabits per second. With a single wavelength, they transmitted at 160 gigabits per second. —P.Y.

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CLIMATE

METHANE FEVER

An undersea methane explosion may have driven the most rapid warming episode of the past 90 million years

Not often does a past geologic event exemplify what the actions of humanity may inflict on the world. Most global changes, such as the waxing and waning of ice ages, take so long that they are indiscernible in human lifetimes. But 55 million years ago a series of methane gas blasts may have choked the atmosphere with greenhouse gases at a pace similar to that at which the burning of fossil fuels pumps them into the air today.

Back then, at the end of an epoch of time known as the Paleocene, temperatures in the deep ocean soared by about six degrees Celsius. This worldwide heat wave killed off a plethora of microscopic deep-sea creatures and produced a bizarre spike in the record of carbon isotopes. Five years ago paleoceanographer Gerald ("Jerry") Dickens of James Cook University in Australia proposed that a belch of seafloor methane—a greenhouse gas with almost 30 times the heat-trapping ability of carbon dioxide—caused the shock. But no one had actually seen evidence of where this catastrophe might have happened—until now.

Dickens, working with Miriam E. Katz of Rutgers University and two other researchers, recently discovered evidence of the exact sequence of predicted methane warming events buried under half a kilometer of sediment off Florida's northeastern coast. "It's the first really tangible evidence of methane release from that time," says marine geologist Timothy J. Bralower of the University of North Carolina at Chapel Hill. "It's almost too good to be true."

Katz, who helped to retrieve the prized seafloor sediment in 1997, was searching initially for the extinction. Some bottom-dwelling creatures called foraminifera, or forams, suffocated in the warmer water because it contains less oxygen than does cold water. Their hard shells were eventually buried in the seafloor muck.

Staring through a microscope for hours at time, Katz painstakingly separated thousands of salt-grain-size forams from their muddy mass grave using a tiny paintbrush. Her search revealed that 55 percent of the species of deep-sea forams had disappeared from the fossil record in a blink of an eye in geologic time—less than 10,000 years within the late Paleocene climate fever. Katz's colleague Dorothy K. Pak of the University of California at Santa Barbara found that the shells of the surviving forams clearly recorded the carbon isotope spike.

Within the foram deathbeds, Katz was startled to notice a 25-centimeter-thick layer of jumbled chunks of mud.

GEOMAR

***FIZZING CHUNKS** of methane hydrate, some refrigerator-size, can tear away from the seafloor and float to the surface before releasing the greenhouse gas trapped inside.*

"At first I complained that it was messing up my extinction event," Katz says. Then she remembered Dickens's idea about what might have caused the creatures to die in the first place: An explosion of methane escapes from seafloor hydrate deposits where the gas, generated as bacteria digest dead plants and animals, lies entombed in crystalline cages of ice. The gas then bubbles to the ocean surface, enters the atmosphere and begins trapping the heat that eventually warms the ocean water and suffocates the forams.

Such an explosion would have likely

triggered a seafloor landslide, and the jumbled mud layer looked like the smoking gun of just such an event. That's when Katz called Dickens into the project. He based his original methane escape scenario on the fact that methane hydrate deposits, which today contain something like 15 trillion tons of gas, are the only place where organic methane exists in abundances that could alter the isotopic signature of the foram shells. When Dickens and Katz searched for the landslide source, they found chaotic sediment layers just downhill from a buried coral reef—an ideal place for gas bubbles to have gathered before freezing into icy hydrates.

Still, not everything is solved. Richard D. Norris of the Woods Hole Oceanographic Institution notes that an abrupt change in deep-ocean currents, rather

BY THE NUMBERS

The U.S. Trade Deficit

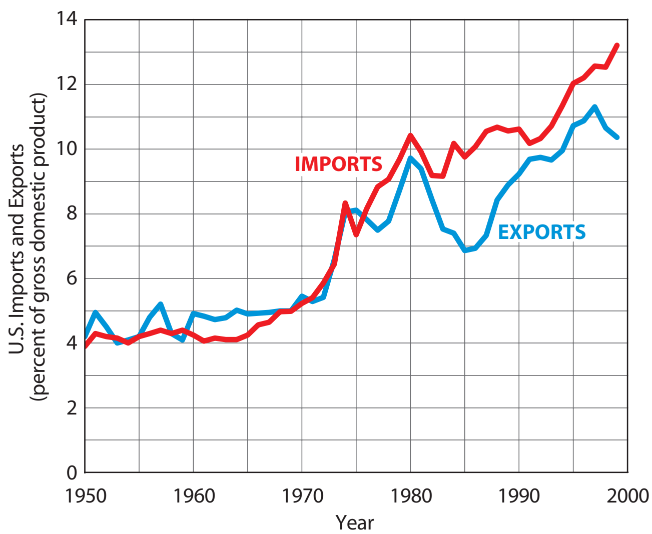
As an indicator, the trade deficit is most peculiar, for it is both a sign of prosperity and a portent of decline. For the past 25 years the deficit rose when times were good and fell during recessions. Exports provide jobs for almost 12 million Americans at above-average wages, while imports contribute to low inflation by offering a variety of goods at modest prices.

But the huge trade deficit, at a record-breaking quarter of $1 trillion in 1999, poses the threat of a large and sudden devaluation of the U.S. dollar if foreign holders become pessimistic about the American economy. That could result in higher prices for imported goods, leading to domestic inflation and, subsequently, to higher interest rates and a slowing of the economy's growth rate.

A major cause of the current high deficit is the disparity between the economy of the U.S., which is growing rapidly, and those of most other countries, which are not. The consequence has been a slackening of demand in these countries for U.S. goods. Another important reason is overspending by U.S. consumers. Today's level of consumer debt, in the opinion of many economists, is particularly worrisome, for it could induce widespread bankruptcy when the economy slows, as it inevitably must. A leading student of the deficit, Catherine L. Mann of the Washington, D.C.–based Institute for International Economics, estimates that the current imbalance can be sustained for two to three years—enough time, perhaps, to put in place measures that would reduce the likelihood of a sudden devaluation. Such measures might include reducing trade obstacles further, training workers better and encouraging consumers to save.

The tremendous expansion of American foreign trade after World War II was facilitated by the General Agreement on Tariffs and Trade (GATT), which dates to 1947, and by the World Trade Organization (WTO), established in 1995. They gave the international trading system a measure of stability and predictability, thus encouraging trade worldwide, which in real terms has gone up more than 10-fold since 1960. The extraordinary increase in American trade beginning in the late 1960s and early 1970s was, according to Mann, the result of several factors, such as the cumulative effect of the reduction in trade barriers, the demand for foreign imports as incomes rose, the more open international financial environment and the internationalization of the production process through foreign investment. The growth of the deficit during the 1980s occurred when the U.S. came out of the 1981–82 global recession faster than other industrial countries did.

Among the goals that the U.S. hopes to achieve in future WTO negotiations are an extension of the moratorium on Internet taxes, the elimination of foreign agricultural subsidies and the strengthening of intellectual-property rights. But these aims may be more difficult to realize now because of demands from the newly resurgent U.S. labor movement. The unions believe, with some justification, that globalization of markets gives employers too much power, because they can threaten to move operations to a low-wage country. The labor movement, together with allies among environmentalists and human-rights activists, demonstrated its strength by persuading the U.S. House of Representatives to reject in 1998 reauthorization of "fast track" authority. (Fast track expedites trade negotiations by compelling Congress to vote on trade agreements without attaching amendments.)



SOURCE: Bureau of Economic Analysis, U.S. Department of Commerce. Included are data for both goods and services. The 1999 data are projections based on the first nine months.

This new coalition wants countries that export to the U.S. to ban child labor and guarantee the right to unionize. It wants protection against WTO actions that infringe on U.S. environmental laws and more transparency in the operation of WTO decision-making panels, which work behind closed doors. Many WTO members, particularly developing countries, vehemently object to including labor and environmental regulation under the WTO umbrella, believing it to be a maneuver by the U.S. to discriminate against their exports. Despite the acrimonious collapse of the Seattle WTO talks this past December, negotiations are likely to resume, for virtually every country has a vital stake in promoting the continued growth of world trade. —*Rodger Doyle (rdoyle2@aol.com)*

RODGER DOYLE

COURTESY OF OCEAN DRILLING PROGRAM

MICROSCOPIC CREATURES, including this foraminifer called **Stensioina beccariiformis,** *died in droves when their ocean-bottom homes heated up during a worldwide climate fever about 55 million years ago.*

than exploding hydrates, could explain the landslide. And what caused the methane to come out in the first place is not clear. One possible trigger is the five-million-year warming trend that led up to the end of the Paleocene and had already poised the planet for dramatic change. When the bottom waters reached a critical temperature, the fragile hydrates may have decomposed in a sudden blast.

Even so, Katz says, it would have taken a series of such blasts to generate the nearly one trillion tons of gas that Dickens calculated would have been necessary to account for the isotope spike. But besides melting, hydrates have another, shorter way of going from the seafloor to the sky. On a research cruise off the coast of Oregon last summer, Erwin Suess of the Research Center for Marine Geosciences in Kiel, Germany, and his colleagues saw refrigerator-size chunks of buoyant methane hydrate that had made a kilometer-long trip from the seafloor to the ocean surface before disintegrating.

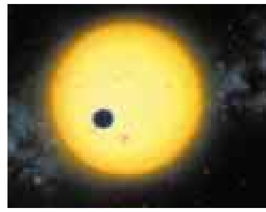
A final question burns in Dickens's mind: "Once we get all of that carbon into the system, how do we get it out?" Understanding the consequences of the late Paleocene warming is crucial for the earth's current inhabitants. Even if we stopped driving our cars and burning coal in power plants today, Dickens says, the carbon dioxide that is already there would still have an impact down the line. *—Sarah Simpson*

In Brief, *continued from page 24*

More Than a Wobble

Astronomers generally infer the presence of extrasolar planets from the wobbling motion of their stars. Now they have witnessed a distant planet passing in front of its star (in this case, HD 209458, 150 light-years away). Using the planet's shadow, researchers measured the planet's size and deduced that it has two thirds the mass of Jupiter and a 60 percent larger radius. The results appeared in the January 20 *Astrophysical Journal Letters.* On the heels of this discovery, a British team reports in the December 16, 1999, *Nature* of having detected reflected starlight from a planet orbiting star Tau Boötis, 50 light-years away. After filtering the planet's light from the star's, scientists estimated the planet to have eight times the mass and to be nearly twice the size of Jupiter and concluded that it is bluish-green in color. Eventually both methods will be used to determine the composition of distant planets and possibly to reveal those suitable for life. *—D.M.*

LYNETTE R. COOK



Out in front

SA

PROFILE

When the Sky Is Not the Limit

In bringing the stars indoors, astrophysicist Neil deGrasse Tyson expands the visitor's universe

The Chilean poet Pablo Neruda summed up his view of fate with the comment, "Every casual encounter is an appointment." Astrophysicist Neil deGrasse Tyson has a similar attitude, whether he is considering galactic evolution or the path of his own life. The 41-year-old Tyson's personal encounters have led him to his current appointment, as Frederick P. Rose Director of the American Museum of Natural History's Hayden Planetarium, which reopens this month. Tyson has been the scientific soul behind the renovation, or more accurately re-creation, of the New York City institution that has brought the universe and the night sky to urbanites for generations.

A strictly deterministic outlook could lead to an overly simplistic telling of the Tyson tale: the kid from the Bronx grew up in the Skyview Apartments, and the rest was history. The rooftop of his building, built on one of the Bronx's highest points, did indeed afford a reasonably good look at the heavens in a light-polluted urban environment. More important, however, was his motivation to take advantage of that rooftop. He was in the fifth grade when the universe descended on him, a tale he tells in his soon-to-be-published memoir, *The Sky Is Not the Limit: Adventures of an Urban Astrophysicist.* He also shares the story with this visitor to his office.

"I had a friend," Tyson recalls, "who had a pair of binoculars. And he invited me to look up with them, something I had never done before. I remember thinking to myself, 'If I look at the moon through these binoculars, the moon will simply be bigger.' But no. It wasn't just bigger, it was better." Even through bird-watcher's binoculars, details of the moon's surface leapt out. "What was formerly this gray, shady orb turned into an actual world, with mountains and valleys and craters and shadows," Tyson says. "And I've been hooked ever since."

Tyson quickly points out, though, that "interest alone doesn't get you anywhere. It requires care and feeding." He ravenously digested any astronomy information he could find, a pursuit supported by his parents and actively enabled by his mother. "I like to think of her as an 'astromom,' " he says. "If I ever needed a lens or a book, she would work to ensure that I got it." He was soon looking at Jupiter's Galilean moons and Saturn's rings, sometimes at the expense of schoolwork. Fortunately, another Nerudan encounter was nigh.

Tyson's sixth-grade science teacher noted his astronomical interest and showed him an ad for a Hayden evening course called Astronomy for Young People. Although he was even younger than the target age for the class, Tyson enrolled. "It opened my eyes to the study of the universe as an academic pursuit rather than as a weekend curiosity," he says. More Hayden classes followed, and his career trajectory was precociously set. Today Tyson has a special pen with which he signs the same certificates he once received for a successful course completion.

SHARING THE MUSIC OF THE SPHERES with museum visitors is Hayden Planetarium director Neil deGrasse Tyson.

Faithful to his Bronx roots, Tyson went on to attend Bronx High School of Science; at the 20th anniversary reunion of his graduating class, the Hayden director was voted by his fellow alumni as holding "the coolest job." In his teens, Tyson read and creatively employed *Scientific American* to mark his career bearing—by studying the authors' biographies. "I got to read what kind of people they were," he says, "and where they got their degrees. It was my first exposure to the academic pathways that enable someone to become an astrophysicist."

The biography of the late astrophysicist David Schramm, who wrote his first *Scientific American* article in 1974, particularly impressed the young Tyson, who was the captain of the Bronx Science wrestling team. "It said [Schramm] wrestled Greco-Roman," he remembers. "He was a big, strapping fellow—I think they called him Schramm-bo. I thought, 'This is cool. I can wrestle and enjoy that and still make a career out of astrophysics.' And so I valued that counterpoint to the articles."

Tyson continued his education at Harvard University and then began his graduate career at the University of Texas at Austin, where he created theoretical models of star formation in dwarf galaxies. He also took a relativity class, taught by John Archibald Wheeler, in which he met fellow student Alice Young. That encounter led to marriage and a daughter, Miranda. Tyson then moved on to

Columbia University, just a few miles south of the Skyview Apartments, for doctoral research on the structure and evolution of the center of the Milky Way, the so-called galactic bulge.

While in graduate school, Tyson began another kind of encounter, with laypeople, by reaching out to share the joys of scientific knowledge. Since 1983 he has written a column for *Star Date* magazine, a general readership publication of the McDonald Observatory of the University of Texas at Austin. In it, Tyson takes on the guise of a mythical character called Merlin (not of Arthurian legend), a native of the Andromeda galaxy. Present on Earth since the planet formed, Merlin teaches science to readers in ingenious ways—for example, by recounting conversations with great thinkers of the past. Two compilations of Merlin essays have been published.

In the early 1990s officials of the American Museum of Natural History resolved to renovate the Hayden, which had fallen behind the times physically and scientifically. Tyson, who had finished postdoctoral research at Princeton University and had become a visiting faculty member there, was already known within the astronomical community as a strong scientist who could also communicate with just-plain-folks. "And that's when I started getting phone calls," he says.

Tyson came to the planetarium in 1994, became its acting director the following year and permanent director the next, all while maintaining a Princeton position and writing a monthly column for the museum's publication, *Natural History.* "He came into our field of vision as someone who was extraordinarily talented as a communicator of science," says Ellen V. Futter, president of the museum. "He really is inspirational in his ability to enliven very complex fields and theories in ways that make them not only accessible but fascinating, intriguing and really exciting."

A highlight of the remade Hayden, now one component of the $210-million Rose Center for Earth and Space, is the unparalleled view of the night sky it can serve up. The planetarium has a new $4-million Zeiss projector, the Mark IX, custom-made for this task. "It can put stars on the dome whose images are so precise that they're smaller than the resolution of the human eye," Tyson says. "That means you can put detail on the dome that your eyes can't see." There is method to this seeming madness. "You can now bring binoculars into the dome and see more with them than you could with the naked eye," he explains. "New Yorkers hardly ever look up. They look down. They're worried about what they'll step in. And even if they look up, they see buildings or smog or the lights on Times Square."

The quest for verisimilitude includes scintillation, twinkling of stars caused by atmospheric turbulence. Though charming, scintillation is a reduction in clarity. Including that feature therefore means investing in technology that lessens the view. Tyson wanted it, however, for its teaching potential. "You can put up the stars, flick the switch for twinkling and put on some lights," he says, "and you start the visitor with the same sky that you would see from the streets of New York. And then you take a drive to the country, and you start dimming the lights and removing the scintillation. And the majesty of the night sky as seen from a mountaintop comes into view." Visitors will also be able to leave Earth, from their seats, and see images of the rest of the universe.


D. FINNIN American Museum of Natural History

***CUSTOMIZED ZEISS PROJECTOR** at the planetarium can duplicate scintillation—the twinkling of stars.*

From the street, the theater's dome is the top half of a 87-foot sphere, which has been completed and encased in a glass cube. "We're using that sphere in a walkaround exhibit where we compare the sizes of things in the universe," Tyson says. Poet and artist William Blake contemplated seeing the world in a grain of sand and holding infinity in the palm of your hand. Holding the world in one's palm becomes a possibility inside the sphere, where a softball-size Earth leads to realizations about the solar system. "On that scale, Jupiter is about 17 feet in diameter," Tyson notes. "And the sphere is the sun. You can see and feel how much bigger the sun is than Earth. And we go out to stars and galaxies, and the other way, down to the chemistry, down to molecules, atoms and atomic structure." The belly of the sphere also re-creates the universe's first three minutes, where guests can observe the big bang and the formation of the light elements.

With the completion of the new Hayden, Tyson will have the chance to return to his first calling, the research that has been on hold during the intensive final stages of planetarium construction. "I remain interested in the structure of the galaxy," he says, "and what we call the kinematics and the dynamics of the galaxy. Not only do stars have a certain abundance of heavy elements, they're moving in a certain direction." That information can indicate how the galaxy "will continue to evolve, or what it must have evolved from," he reveals. Tyson will resume this exploration as curator of the Hayden's new, academic astrophysics department, which has two other researchers in place and postdocs arriving in the fall. "We're being born whole in a way," he says, "with an infrastructure that will support a scientific research program." Although he will maintain his director's seat, Tyson will also make more time for science by handing over some of his duties to James S. Sweitzer, formerly assistant director of Chicago's Adler Planetarium and now director of special projects for the Rose Center for Earth and Space.

Even ensconced in research, Tyson will no doubt often be as visible as Venus on a clear night just after sunset. He enjoys and feels a particular responsibility to appear before the public, dating back to his first experience watching himself on television. During his time at Columbia, astronomers detected massive prominences and flares on the sun. A local news outlet called the school, and Tyson was asked to discuss the explosions. He watched the taped segment that evening. "I realized I had never before seen a black person on television who was being interviewed for expertise that had nothing to do with being black, other than entertainers or athletes. And at that point I realized there's no greater obligation I have than to continue to be an expert when the media has questions about the universe—thereby possibly exploding stereotypes." Through his study of the entire universe, Tyson has thus been led to the ultimate Nerudan encounter—an appointment with himself.

—Steve Mirsky in New York City

ANIMAL EXPERIMENTATION

VIOLENT OPPOSITION

Escalating protests may be driving away some researchers

For scientists trying to find a cure for cancer or AIDS or to uncover the mechanisms behind aging or depression, controversy over animal experimentation comes with the territory. But last year 80 U.S. scientists received a personal and potentially bloody taste of the battle in their mailboxes: letters armed with razor blades, attached in such a way that a finger would get a nasty cut if slid beneath the envelope flap. Although no one was injured, the incident was a wake-up call concerning the escalating illegal activities against researchers, laboratories, animal breeders and even feed suppliers.

"I don't think a week's gone by that I haven't heard of a scientist being threatened or intimidated," says Jaqueline Calnan, president of Americans for Medical Progress, a U.S.-based defender of animal research. The attacks are not only taking a financial and research toll, but some investigators now believe scientists are abandoning the field.

The Animal Liberation Front (ALF), which advocates illegal, nonviolent activism, was responsible for dozens of attacks in North America last year. It took credit for $750,000 in damage to offices and equipment at the University of Minnesota, where researchers study Alzheimer's disease and work on a vaccine against brain cancer. Other targets were the University of California at San Francisco, where many data, including work aimed at developing alternatives to animal research, were lost, and Western Washington University, where three dozen research rats and rabbits were stolen. ALF proudly stated that it destroyed one scientist's lifetime of work there.

The razor letters are especially frightening because they strike on a personal level. Eight went to University of Wisconsin–Madison researchers, which simply heightened the tension between investigators and protesters, notes Joseph W. Kemnitz, director of the Wisconsin Regional Primate Research Center. The home visits were particularly unsettling: Kemnitz and his family left town after protesters held candlelight vigils, wrote epithets in wax on his sidewalk and car, and drummed and shouted insults.

Many worry that U.S. activists are importing tactics used in 25 years of British violence. Animal-rights terrorism there has caused more than $200 million in property damage over the years and cost millions in policing and security annually, says Colin Blakemore, director of the University of Oxford's Center for Cognitive Neuroscience. Blakemore himself became a target 12 years ago while using kittens in vision research. A razor package injured his secretary, and his three children required 24-hour security after kidnapping threats and bomb scares. Blakemore was beaten, his home was vandalized, and massive demonstrations against him at one point brought out 200 police in riot gear. He still makes no public move without a police escort.

JOSEPH SOHM *ChromoSohm, Inc./Corbis*

***PEACEFUL PROTESTS,** such as this one at the University of California at Los Angeles, are giving way to more vicious actions, such as booby-trapped mail and arson.*

"In a way, terrorists are winning," Blakemore concludes. Activists have closed animal suppliers, won minor legislative victories, such as a rule banning alcohol or tobacco testing on animals, and created an uneasy climate for research. Then there is the human impact. "Students are not choosing to come into the arena of science involving animal research," Blakemore remarks. "There's a withering of that branch of science."

That attitude may not be apparent in the U.S.—yet. Richard W. Bianco, director of experimental surgery at the University of Minnesota, has noticed that researchers have begun asking, "'Why am I bothering?' Graduate students are nervous. Who knows how many people don't go into science because of it." Moreover, Bianco sees a changing culture ending open access to research as thousands are being spent on key cards, additional cameras and lighting, and faculty education.

The Federal Bureau of Investigation refuses to discuss active domestic terrorism cases but hints that, despite few arrests, it takes recent events seriously. But it is also incumbent on mainstream animal-rights groups to disavow illegal activities, insists Christopher Coe, director of the Harlow Center for Biological Psychology. Instead the head of People for the Ethical Treatment of Animals suggested in recent news interviews that scientists deserve to be targets of violence. Merritt Clifton, editor of *Animal People,* an animal-protection publication, says most groups fail to condemn ALF for fear of alienating donors, who maintain a Robin Hood image of the organization, even though ALF "gets in the way of any kind of progress in any positive direction."

Coe thinks animal welfare, where the animal-rights movement has made a positive difference, should be the issue. "I told one group, 'For every dollar you raise to improve conditions, I'll put it directly into animal welfare.' No one has taken the offer." *—Meg Turville-Heitz*

MEG TURVILLE-HEITZ is a writer and an environmental science editor based in Madison, Wis.

PLEASE DISPOSE OF PROPERLY

Entrepreneurs look for ways to put old computers to good use

Where do old computers go when they die? Most likely into a closet, piled out of sight and mind to make way for new Pentiums and laser printers. Or else deep into a landfill, buried beside hot dogs and newspapers that are still recognizable years later. It could be a dangerous tomb: lead, mercury and chromium inside computer carcasses could leach into the soil, sickening the surrounding ecosystems. The bottom line is that with processor speed doubling every 18 months or so, described as Moore's Law, people are buying new machines almost as often as they update their wardrobe. The result, according to a 1997 Carnegie Mellon University study, is that 150 million dead but not decaying PCs will be buried in U.S. landfills by 2005.

"It's a problem a lot of people just didn't know we had," says Bob Knowles, founder of Denver-based Technology Recycling. "My biggest challenge is letting people know that there's eight pounds of lead in a monitor and three to five pounds in a CPU," or central-processing unit.

The Environmental Protection Agency permits individuals to pitch computers, which are categorized as household hazardous waste, but the business world may be getting more than it bargained for when it upgrades. The EPA requires them to handle the machines (in particular, the monitors and batteries) in compliance with the U.S. Code's Resource Conservation and Recovery Act, which sets regulations on the disposal of solid and hazardous waste.

A National Safety Council study estimates that 20.6 million PCs fell into disuse in 1998 but that only 11 percent were recycled. Dozens of waste management firms, new and veteran, are diving into the electronics recycling waters by charging to properly deal with high-tech detritus—in effect, making companies pay an obsolescence tax.

Technology Recycling is one of many firms that make their money from Moore's Law. For $35 per CPU, monitor or printer, one of Knowles's teams collects and disassembles the PCs. Once extracted, the precious metals and hazardous materials are processed by EPA-approved facilities and eventually sold in the spot-metal market. Plastics and glass are recycled into building materials. Another recycler, Conigliaro Industries in Framingham, Mass., has developed a process to convert PC casings into pothole filler.

If the thought of a system that cost you $2,000 only five years ago being shoveled into a furnace or used to pave highways is abhorrent, consider that the other option, donating PCs to charity, does not always earn a pat on the back, either. "Some of the recipients want the donation only if it's the latest and greatest model," comments David Isaacs, director of environmental affairs for the Electronic Industries Alliance. "But there are still users who can benefit from older models. Reuse is still an important option."

Statistics seem to be proving Isaacs right. The Carnegie Mellon projections of the number of computers in landfills are actually downward amendments to a 1991 study. The study cited the "second life" given to computers by the growing market for reused and recycled electronic components as a key factor that lowered its original estimates.

Meanwhile the European Commission's Directive on Waste from Electrical and Electronic Equipment, still in its proposal stage, is intended to make the PC industry overseas greener. The directive calls for, among other things, a ban beginning in January 2004 on materials such as lead-based solder in PCs and the imposition of recycling responsibilities on manufacturers.

"We do not think that it's appropriate under these circumstances to legislate high-tech design," Isaacs says. "There are emerging substitutes for lead in some applications, but there's not an across-the-board alternative." Furthermore, Isaacs adds, putting the financial and logistical onus of recycling on electronics manufacturers oversimplifies the problem: "You're also going to need the existing collection and transportation infrastructure, component manufacturers, raw materials suppliers and recyclers to play a role."

And that's the aim of the International Association of Electronics Recyclers (IAER). Formed last year, the trade association wants to bring the concerned parties to the table to establish environmental standards, develop technology for cost-effective recycling and build an effective infrastructure "for managing the life cycle of electronics products," according to its Web site.

H. R. BRAMAZ Peter Arnold, Inc.

***OLD COMPUTER EQUIPMENT** contains lead and mercury, which could poison ecosystems if left in landfills. The guts, though, can be scavenged and recycled.*

Who will pay for keeping that infrastructure cranking is still up in the air, IAER founder Peter Muscanelli admits. But no matter who foots the bill, he says, the bigger question to consider when it comes time to retire your old PCs is this: "If we have the ability to recycle, and we don't do it, what are we going to [do with] that material 100 years from now?" —*David Pescovitz*

DAVID PESCOVITZ, based in Oakland, Calif., specializes in computers and information technology.

HEALTH

ASBESTOS IN THE AIR

A housing boom stirs up natural asbestos in California

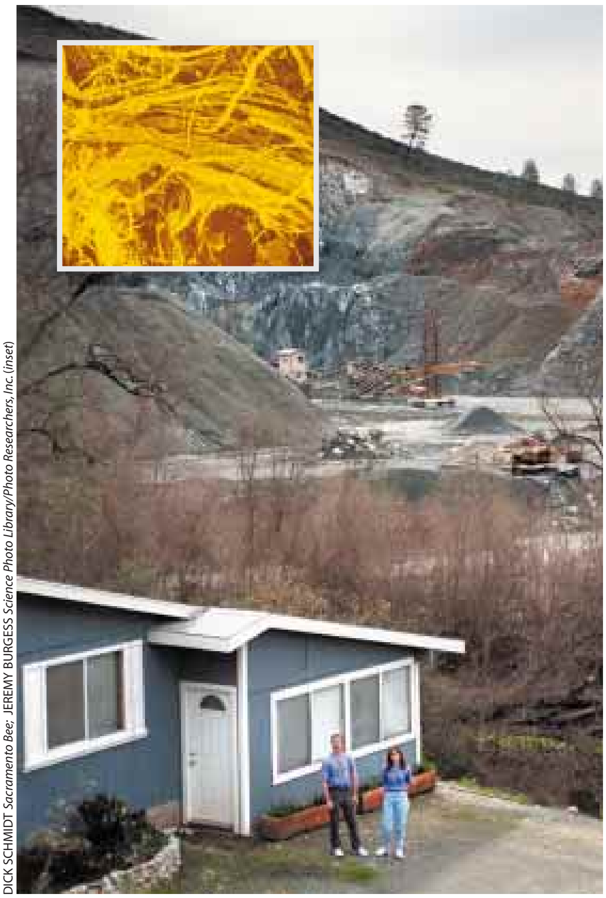
There's a new gold rush in California's Sierra Nevada foothills—a rush to build homes. Tens of thousands of new residences have been approved for the area recently, and every day heavy machines carve out another future front yard. But the building boom that is transforming the once rural western part of El Dorado County into a suburb of Sacramento has also unearthed a health hazard: asbestos. Although government agencies say the area is safe, citizens and environmental experts argue that the agencies may be vastly underestimating the risk.

A known human carcinogen, asbestos is highly regulated in buildings. For instance, building waste that contains more than 1 percent asbestos is considered hazardous waste. Yet exposure to naturally occurring asbestos is largely unregulated. "Just 1 percent is hazardous waste, but it's supposed to be okay for people to live on a 90 percent deposit," complains Lance McMahan, a civil engineer and hazardous-waste site manager who recently moved out of the area because he believes that the health risk is unacceptable.

The issues confronting El Dorado County could surface elsewhere in the U.S. as development pushes further into new regions. Serpentinite, which is California's state rock, occurs in many regions of the western U.S. and along parts of the East Coast. A feature of faulted mountain-building areas, serpentinite and asbestos are also found in Greece, Turkey, Cyprus and Corsica, where high levels of environmental exposure have resulted in respiratory diseases, including several forms of cancer.

Two types of asbestos, chrysotile and tremolite, occur in the serpentinite rock that underlies the western Sierra Nevadas. Left below the surface, it is not a problem. But when the serpentinite is dug up and used to cover unpaved roads or when new homes are cut into the hillsides, asbestos fibers get into the air. Combine these activities with a rapidly growing population—expected to double to 225,000 by 2018—and the potential for disease becomes real. Of particular concern is mesothelioma, a fatal cancer of the membranes lining the chest, which has been linked to tremolite exposure.

Naturally occurring asbestos is supposed to be a local planning issue, state and federal officials say. Unfortunately, El Dorado County has historically ignored or denied the issue, according to recently elected county supervisor W. Sam Bradley. A 1998 investigation by the *Sacramento Bee* found levels of tremolite asbestos fibers more than 20 times higher than the federal health limit for airborne asbestos in schools. Thanks to the report, the California Air Resources Board (CARB) stepped in.



DICK SCHMIDT *Sacramento Bee;* JEREMY BURGESS *Science Photo Library/Photo Researchers, Inc. (inset)*

***ASBESTOS EXPOSURE** is a risk faced by residents forging into El Dorado County, such as Jim and Toni Johnson, who live near a quarry that crushes rock containing tremolite* (inset), *a highly dangerous form of asbestos.*

Since 1998 CARB has been conducting ambient, or background, air monitoring. The highest 24-hour measurement, when plugged into the Environmental Protection Agency's health-risk equations, yields estimates of an increased risk of mesothelioma of 290 in a million and lung cancer of 170 in a million. In comparison, CARB estimates that contaminants in urban air are responsible for 500 lung cancers in a million.

Many believe, however, that the situation is far worse than the monitoring suggests. Exposure to asbestos does not occur continuously, they observe; instead the exposure is local and episodic. Children are exposed, for example, when playing in the dust, and high levels of asbestos can be kicked up when cars travel down unpaved roads or neighbors landscape their backyards. Moreover, "there is a vast body of knowledge to say that ambient monitoring simply does not reflect human exposure," maintains Stanford University's Wayne R. Ott, who specializes in exposure monitoring.

A risk assessment that accounts for episodic exposure is "easier said than done," responds Melanie Marty of California's Office of Environmental Health Hazard Assessment, which is advising CARB. What's best, she says, is to develop regulatory controls to stop asbestos from entering the air. Several California counties and Fairfax County, Virginia, already have such rules, such as requiring the suppression of dust with water and the burial of exposed serpentinite rock. CARB staff are trying to develop rules to decrease emissions from asbestos sources—quarries, road dust and construction activities. The board expected to vote on such statewide measures in July.

For McMahon, however, the promise of such measures is not enough. The situation in El Dorado County, he remarks, "is worse than any site I've ever looked at. It will take years to build a consensus about what to do and then even more years to do it. As far as I'm concerned, it is time to get out." *—Rebecca Renner*

REBECCA RENNER is a geologist turned science writer. She is based in Williamsport, Pa.

WIRELESS TECHNOLOGY

TIME OUT

A Patent Office ruling frees the development of new ultrawideband wireless systems

Both sides were claiming victory late last year in a seething dispute over patents that could be worth billions covering potentially revolutionary low-power radars and communications devices. The dispute had pitted a small privately held company, Time Domain Corporation in Huntsville, Ala., against Lawrence Livermore National Laboratory and even resonated in Congress, where two members championed Time Domain's cause.

The roots of the affair go back to the 1970s, when Larry Fullerton, now of Time Domain, invented a radar and wireless system based on pulses of energy less than a billionth of a second in duration. The scheme is known as ultrawideband. Although ultrawideband pulsed radar has been around for decades, the U.S. Patent and Trademark Office decided in 1987 that Fullerton's system was original enough to be patented.

The way it works is that the transmitter retards or advances individual pulses by an instant to represent 0s and 1s, using a coding scheme. The receiver knows the code and decides whether a pulse is a 1 or a 0 by timing its arrival. Resistant to most interference, the ultrawideband system does not take up bandwidth like conventional wireless systems, so many users could talk in the same area simultaneously. Used as a radar, the system can detect moving objects, because they advance or retard the pulses, so it could help automobiles avoid collisions. It could also track users' locations. Time Domain plans to sell a system that police could use to detect people through walls; it also foresees applications in military communications because of the stealthy nature of the signals: they are indistinguishable from background noise without the right receiver.

In the early 1990s, however, Thomas E. McEwan, then an employee at the Livermore lab, came up with a related idea for a "micropower impulse radar" that employed different circuitry and worked at much lower power. His device can function for years on a couple of penlight batteries, he states. He got patents, too, and assigned them to his employer, which started licensing the invention to manufacturers. But McEwan failed to cite Fullerton's invention as "prior art" in his original patent application.

Inventors must cite any related work they know of in patent applications, so Time Domain cried foul. As McEwan had been at a technical conference where Fullerton's work was described, the company charged that McEwan had misappropriated its technology, and its president, Ralph G. Petroff, who has invested several million dollars of his money in Time Domain, declared that McEwan's patents should be ruled invalid. To resolve the matter, Livermore and Time Domain asked the Patent Office to reexamine the McEwan/Livermore patents.

Claims and counterclaims flew. Then Congress got into the act. The Democratic minority staff of the Committee on Science, U.S. House of Representatives, with the encouragement of Senator Richard Shelby and Representative Robert E. Cramer, Jr., both of Alabama, compiled a report entitled "Spinoff or Ripoff?" It criticized Livermore for not citing Fullerton's prior art, for misrepresenting micropower impulse radar's status with the Federal Communications Commission (FCC) and for overstating capabilities to licensees. Many of Livermore's licensees have had difficulty getting their devices to work, according to the document.

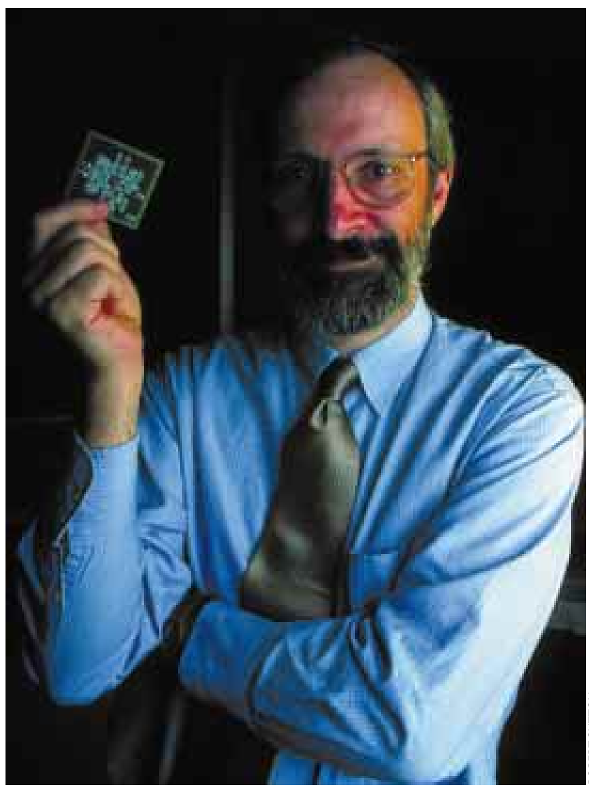
The Patent Office, under pressure to make a decision, issued in December a ruling that seems to upend Time Domain's position that McEwan's patent is invalid: the office allowed 49 of 53 of Livermore's patent claims to stand unchanged; Livermore then withdrew the other four. The office ruled that the Fullerton and McEwan technologies are distinct enough for both to be patentable, a decision that McEwan hails as a vindication.

McEwan has also been granted additional patents for a modification that overcomes a regulatory hurdle for his original invention. That device transmits some of its signal, like Time Domain's, in wavebands that are restricted for other uses, such as aircraft communications. So the FCC has thus far been reluctant to allow ultrawideband devices for the mass market. But the new McEwan scheme, wideband pulsed radio-frequency radar, emits over a narrower range of frequencies and so complies with existing FCC regulations. McEwan now has a company aimed at developing microradar motion sensors and range finders. Livermore's technology-transfer practices have been revamped in response to the criticisms in the congressional report to provide better patent advice to lab inventors.

But Time Domain doesn't see the outcome as a setback. Irving R. Rappaport, a patent adviser to the company, maintains that the history of the reexamination narrows the legal interpretation of McEwan's patent so that it "has now essentially been gutted." Time Domain owns the "fundamental patents," the company insists, and it has also developed newer versions of its technology. Various users are testing prototype secure communications links and search radars. Time Domain could also come out of regulatory limbo: the FCC has said it will soon make a ruling on permissible uses of ultrawideband radars.

With the patent battle over, it seems the contest between the Fullerton and McEwan approaches will now play out in the market. Whichever comes to dominate, small radars will probably be coming soon to a store near you.

—Tim Beardsley in Washington, D.C.



ROBERT SUTTON

***WIRELESS WONDER,** called a PulsON chip, is held by Larry Fullerton of Time Domain.*

MEDICINE

GENE THERAPY SETBACK

A tragic death clouds the future of an innovative treatment method

Eighteen-year-old Jesse Gelsinger died at the University of Pennsylvania last September 17, four days after receiving a relatively high dose of an experimental gene therapy, a novel and unproved technique that aims to correct genetic diseases and other conditions. Gelsinger's death was apparently the result of an overwhelming immune reaction to the engineered adenovirus that researchers had infused into his liver. He died of acute respiratory distress syndrome and multiple-organ failure.

The trial, led by James M. Wilson, director of Penn's Institute for Human Gene Therapy, had sought to test in patients the safety of a possible treatment for an inherited liver disease, ornithine transcarbamylase deficiency (OTCD). Gelsinger had been healthier than most men with OTCD, which causes ammonia to build up in the blood. His illness was being partly controlled with a low-protein diet and with a chemical therapy that helps the body eliminate ammonia—co-invented, ironically, by one of his doctors in the fatal experiment.

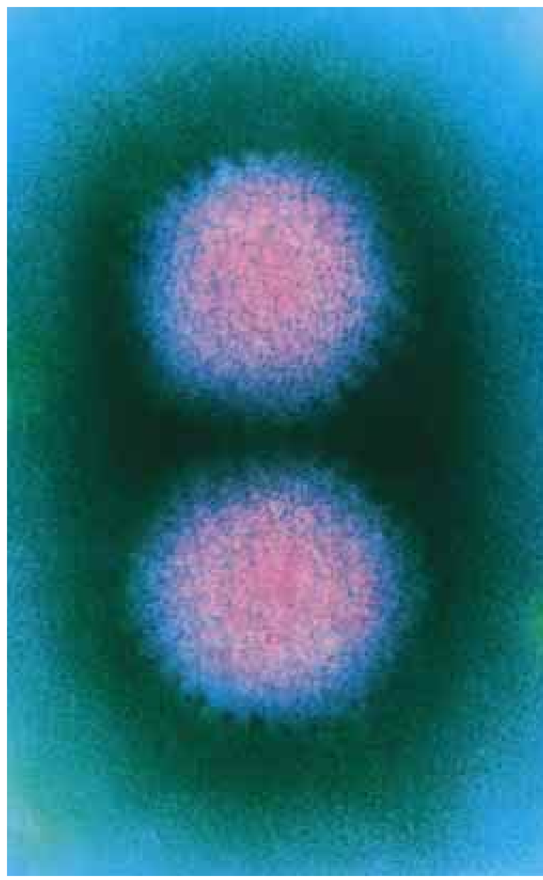
The death triggered alarm at many medical centers that are testing gene therapy, because fully 30 percent of all such trials use adenoviruses to convey a gene into patients' cells, according to Kathryn Zoon of the Food and Drug Administration. Wild adenoviruses can cause various illnesses, including colds and conjunctivitis, although infections are usually mild. The FDA immediately halted two other trials that involved infusing adenoviruses into patients' livers.

Alarm turned to dismay when the Penn researchers admitted at a meeting of the public Recombinant DNA Advisory Committee (RAC) last December that they had failed to notify the FDA prior to Gelsinger's fatal reaction of the deaths of some monkeys that had been given high doses of a different modified adenovirus. And that was only the beginning.

The group had also omitted to tell the RAC of a perhaps crucial change in the way the virus was to be delivered. Most troubling, patient volunteers who participated in the OTCD trial before Gelsinger—but who were mostly given lower doses of virus—suffered significant liver toxicity that, had it been reported to the FDA, would have put the study on hold. Wilson's team acknowledged that it should have called the agency about these findings. Gelsinger himself, it appears, should never have been allowed to enroll at all: the approved protocol called for a female in his slot, because females are less severely affected by OTCD than males. Furthermore, his blood ammonia level was too high for admission into the trial when it was last checked, on the day before the disastrous gene treatment, although it had been within acceptable limits when he was first enrolled. The litany of lapses means that Wilson's Institute for Human Gene Therapy could be sent a formal FDA warning. Subsequent deviations might then disbar his institution from receiving federal funds.

Some clues have emerged to suggest why Gelsinger suffered such an extreme reaction, which was quite different from

KARI LOUNATMAA *Science Photo Library*



ADENOVIRUSES, modified to deliver healthy genes, can spontaneously mutate, perhaps leading to unknown effects. Such a virus seems to have led to the death of patient volunteer Jesse Gelsinger.

the liver toxicity the researchers had noted in monkeys and in previous volunteers. He may have had an undetected infection with a parvovirus that sensitized him to adenoviruses. And the Penn researchers have disclosed that the virus in the lot Gelsinger received had spontaneously undergone a small genetic alteration. Although testing indicates that the previously unrecognized change was of no consequence, Inder Verma, a gene therapy expert at the Salk Institute for Biological Studies in La Jolla, Calif., said at the RAC meeting that he felt the finding was "disturbing," because small changes in a therapeutic virus might have nonobvious effects. Verma has long argued that investigators should include in gene therapy protocols detailed studies of volunteers' reactivity to any viruses involved.

Just as worrisome, the virus given Gelsinger was discovered to have spread far beyond his liver, where it was supposed to correct the defect in his cells. Within the liver it had bound to immune cells far more than to the hepatocytes it was meant to target. Only three of 17 patients treated before Gelsinger showed any sign of benefit. The results are prompting an exhaustive reexamination of the safety of all virus-based gene therapy trials, and researchers are likely to be wary of administering high doses of adenoviruses.

Quite apart from the scientific setbacks, the sad event in Pennsylvania has pushed onto center stage the thorny issue of when deaths in gene therapy trials should be revealed. Patients elsewhere died in unrelated gene therapy trials last year without the deaths being reported to the RAC, as federal guidelines require, although they had been communicated to the FDA, which keeps all data confidential. Other deaths had been divulged to the RAC with requests from the trials' commercial sponsors that they be kept secret. Other than Gelsinger's, the deaths were most likely unrelated to the therapy under investigation. Yet the matter has energized the RAC to seek to disallow confidentiality restrictions and to be notified of all adverse reactions in gene therapy trials. The Biotechnology Industry Organization, however, pointing to the need for commercial as well as patient confidentiality, opposes such measures. The only certain thing during these dark days for the field is that many vital scientific and regulatory issues have yet to be resolved before gene therapy can become good medicine.

—*Tim Beardsley in Washington, D.C.*

Your First $20 Free!

If you're a typical consumer, your electronic mailbox has been sinking under a steady stream of offers from on-line merchants. By clicking on a link or typing a code, you can get 10 or 20 percent off your next order, free shipping for life, a $10 credit or any number of other incentives to shop on the Web. Sites have sprung up to disseminate the offers with names such as dealoftheday.com and virtualbargains.com, and informal networks of shoppers trade information on offers that, properly combined, can leave stores owing you money for having shopped there. Cumulative marketing budgets of these sites are in the hundreds of millions of dollars.

These kinds of come-ons have been part of the "brick-and-mortar" retail world since time immemorial: a loss-leader will get shoppers into a store, where they will buy a host of additional items on the spot rather than drive across town to compare prices. On the Web, however, commerce is supposed to be "frictionless"—competing stores are only a few clicks away, so there is little reason to avoid comparison shopping. There are even sites that do nothing *but* provide comparative price information.

So are on-line retailers crazy? Are they throwing their investors' money away hand over fist? On the contrary. Faced with the enormity of choices on the Web, people are less likely to make solid comparisons than they are in person, says Dan Ariely of the Massachusetts Institute of Technology: they retreat to the few sites they've already bookmarked and buy there regardless of who offers the best price or service. Last year an average book or compact disc cost about $2 more at Amazon.com (which commands about 80 percent of the market) than at Books.com (with about 2 percent), according to Erik Brynjolfsson, also at M.I.T. In fact, Brynjolfsson and his colleagues found that prices varied more widely on the Internet than at the brick-and-mortar stores they surveyed. Customers appear to be willing to pay for the security and familiarity that a well-known name gives them, especially because they don't have physical cues such as the condition of a storefront or the attitudes of the clerks. Profit, Ariely says, lies in reducing consumers' sense of uncertainty.

Indeed, Gal Zauberman of Duke University has run a series of experiments showing that people will stick with their first choice of search engine, bookstore or other Web service even in the face of evidence that another choice would be better or cheaper. Sites with low setup costs are much more attractive, he points out, because surfers want to get something done quickly, before a deadline strikes or their computer crashes. Many commercial Web sites require a lengthy registration process before delivering their goods—anywhere from 10 or 15 minutes to nearly an hour.

In addition, users must spend even more time to master the idiosyncrasies of a particular site's organization, page layout and search engine, Web guru

DAVID SUTER

Jakob Nielsen notes. You can't just wander the aisles of a virtual store to get a sense of where products are. Nielsen's studies indicate that most people are willing to spend only one or two minutes figuring out how to use a Web site unless it provides an immediate payoff of some kind. The only frictionless part of Web commerce, he quips, is people clicking away from a site they don't like.

To hook newcomers, a site must either follow the design rules embodied by existing sites or else be roughly twice as easy to use, he says. (Such an improvement is well within reach, he observes, because many sites are hard even for experts to figure out.) Or it must offer some other incentive. Seen in this light, a credit of $5 to $20 may be fair compensation for the time lost in switching to a new merchant portal or search engine.

Furthermore, once consumers have invested the time to find out whether a new site is better than the old one, they are unlikely to switch back, so it's in the interest of Web merchants to offer incentives to their current customers as well. Whoever is still standing when the venture capital runs out—so the current theory goes—will be among the winners. The total share value at stake among the Internet companies fighting these brand-recognition wars is about half a trillion dollars, Brynjolfsson states.

It's not just a matter of establishing brands before the money runs out and companies have to make profits, Brynjolfsson and his colleagues argue: there is a technological threat that could make current Internet brands obsolete. Ariely is one of those working on so-called intelligent agents that will not merely compare prices but levels of service—they may even choose new products for you based on knowledge of your preferences. For example, he predicts, you might tell your agent you want to buy some wine, and it could suggest a particular varietal and vineyard based on characteristics of your previous purchases. The identity of the wine merchant who fulfilled the order might be completely irrelevant.

Along with agents running on your computer (or perhaps in competition with them), there will also be "infomediaries"—entities Brynjolfsson and Zauberman liken to *Consumer Reports* or Underwriters Laboratories—that vouch for merchants to consumers, and vice versa. Such organizations would go well beyond the simple price comparisons available today to rate service quality, delivery schedules, reliability and so on. They would tell you everything you might want to know before entrusting your time and money to an anonymous bundle of bits.

Such agents, whether local or networked, would end up knowing a great deal about their users and exercising a powerful influence over their choices, Ariely explains, and the companies that build them should be highly profitable. So how will we choose the most useful and responsible agents, given that switching from one to another could be quite difficult? Let's hope that there will be more to the decision process than just relying on the comfort of a well-established brand-name. —*Paul Wallich*

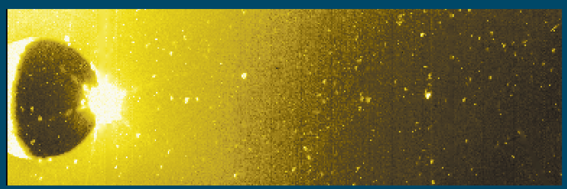
The Galileo Mission to Jupiter and Its Moons

Few scientists thought that the Galileo spacecraft, beset by technical troubles, could conduct such a comprehensive study of the Jovian system. And few predicted that the innards of these worlds would prove so varied

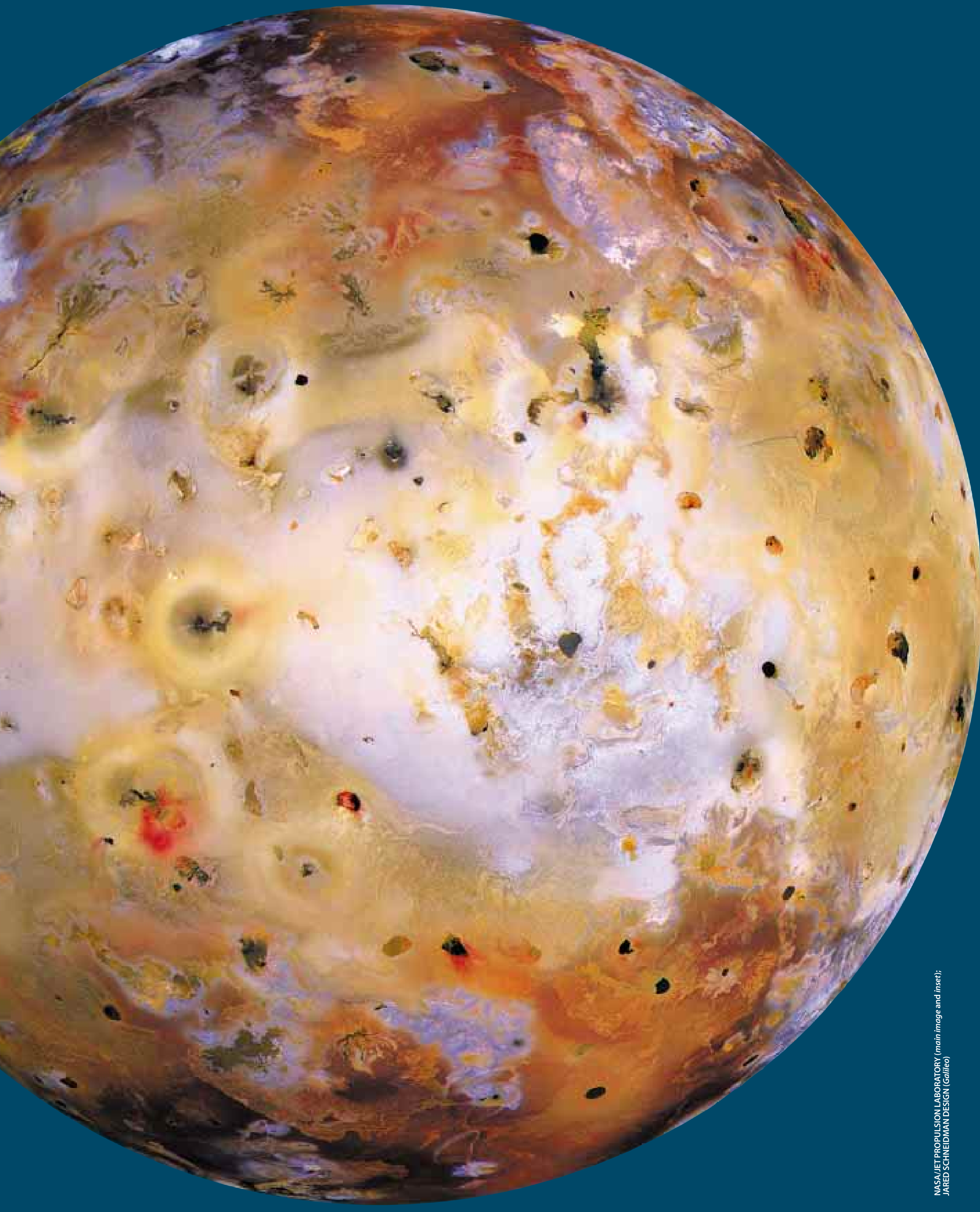
by Torrence V. Johnson

To conserve power, the probe was traveling in radio silence, with only a small clock counting down the seconds. Racing 215,000 kilometers overhead, its companion spacecraft was ready to receive its transmissions. Back on Earth, engineers and scientists, many of whom had spent most of two decades involved in the project, awaited two key signals. The first was a single data bit, a simple yes or no indicating whether the little probe had survived its fiery plunge into Jupiter's massive atmosphere.

Getting this far had not been easy for the Galileo mission. When conceived in the mid-1970s, the two-part unmanned spacecraft was supposed to set forth in 1982, carried into Earth orbit on board the space shuttle and sent onward to Jupiter by a special upper rocket stage. But slips in the first shuttle launches and problems with upper-stage development kept pushing the schedule back. Then came the *Challenger* tragedy in 1986, which occurred just as Galileo was being readied for launch. Forced by the circumstances to switch to a safer but weaker upper stage, engineers had to plot a harrowing gravity-assist trajectory, using close flybys of Venus and Earth to provide the boost the new rocket could not. From launch in October 1989, the journey took six years. Two years into the flight, disaster struck again when the umbrellalike main communications antenna refused to unfurl, leaving the spacecraft with only its low-capacity backup antenna [see "The Galileo Mission," by Torrence V. Johnson; SCIENTIFIC AMERICAN, December 1995]. Later, the tape recorder—vital for storing data—got stuck.



WRACKED BY EIGHTY VOLCANOES, the surface of Io makes Earth look geologically inert by comparison. The yellow, brown and red patches on this false-color mosaic (*main image*) represent different sulfur-based minerals—in other words, brimstone. A sulfur dioxide frost coats the white areas. Gas and dust have been swept into orbit, as is evident when the sun illuminates Io from the side (*inset at right*). Much of the yellowish glow comes from sodium gas. The burst of white light is sunlight scattered by the plume of the volcano Prometheus.



NASA/JET PROPULSION LABORATORY (*main image* and *inset*); JARED SCHNEIDMAN DESIGN (*Galileo*)

The Gas Giant

Jupiter

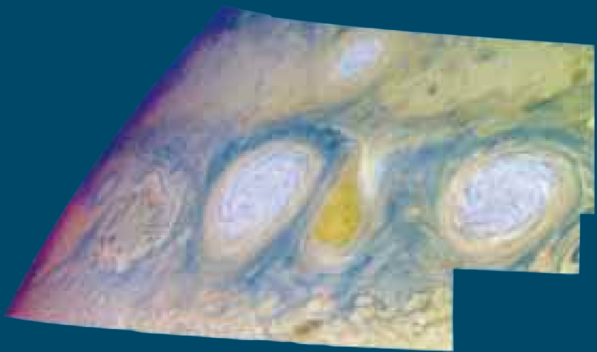
RETA BEEBE *New Mexico State University* AND NASA

Until the Galileo mission, no object touched by human hands had ever made contact with a gas giant planet. The spacecraft dropped a probe into the atmosphere just north of the equator, a location shown on this Hubble Space Telescope image taken after the probe had been targeted (*left*). The probe descended for more than an hour, measuring the composition (*table below*) before succumbing to the increasing temperature and pressure (*sequence at right*). The primordial solar composition is assumed to be the same as that of the outer layers of the sun.

CHEMICAL COMPOSITION OF UPPER ATMOSPHERE
(Number of atoms per atom of hydrogen)

ELEMENT	CHEMICAL FORM	JUPITER	SATURN	SUN
HELIUM	HELIUM	0.078	0.070 ± 0.015	0.097
CARBON	METHANE	1.0×10^{-3}	2×10^{-3}	3.6×10^{-4}
NITROGEN	AMMONIA	4.0×10^{-4}	$3 \pm 1 \times 10^{-4}$	1.1×10^{-4}
OXYGEN	WATER	3.0×10^{-4}	unmeasured	8.5×10^{-4}
SULFUR	HYDROGEN SULFIDE	4.0×10^{-5}	unmeasured	1.6×10^{-5}
DEUTERIUM	DEUTERIUM	3×10^{-5}	3×10^{-5}	3.0×10^{-5}
NEON	NEON	1.1×10^{-5}	unmeasured	1.1×10^{-4}
ARGON	ARGON	7.5×10^{-6}	unmeasured	3.0×10^{-6}
KRYPTON	KRYPTON	2.5×10^{-9}	unmeasured	9.2×10^{-10}
XENON	XENON	1.1×10^{-10}	unmeasured	4.4×10^{-11}

SOURCES: SUSHIL K. ATREYA *University of Michigan*; HASSO B. NIEMANN *NASA Goddard Space Flight Center* AND COLLEAGUES



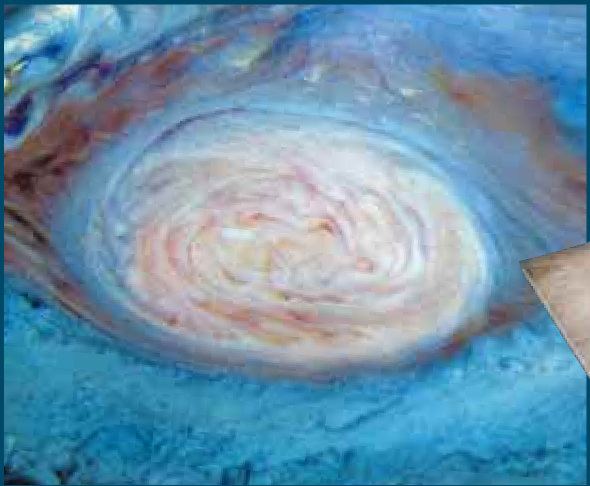
NASA/JET PROPULSION LABORATORY

OVAL CLOUDS were seen by Galileo in early 1997. They have trapped a pear-shaped region between them. The ovals rotate counterclockwise; the pear-shaped region, clockwise. On this false-color mosaic of three near-infrared images, bluish clouds are thin, white ones are thick, and reddish ones are deep. A year later the ovals merged together—a vivid example of Jupiter's dynamic weather. Each oval is about 9,000 kilometers across.

NASA/JET PROPULSION LABORATORY

HOLE IN THE UPPER CLOUD DECK reveals the comparatively warm regions deeper down. As on other near-infrared images, bluish clouds are thin, white ones are thick, and reddish ones are deep (*diagram at right*). The Galileo probe entered just such an area, known as a hot spot. This image depicts an area 34,000 kilometers across.

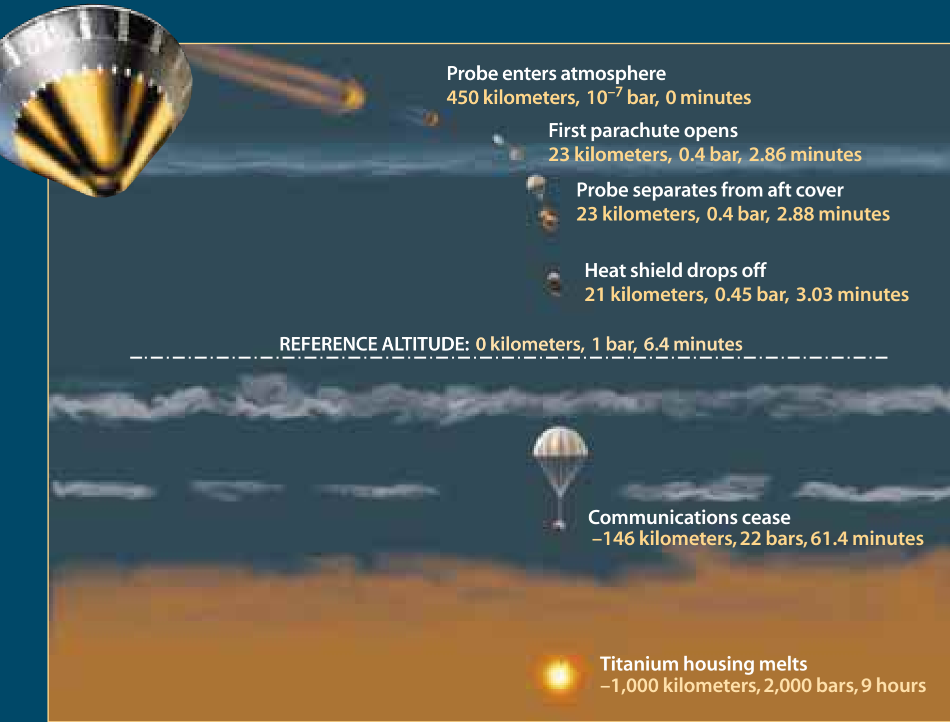
GREAT RED SPOT is a vast storm system that towers some 30 kilometers above the surrounding clouds (*left*). From red to green to blue, the color coding is decreasingly sensitive to the amount of methane along the line of sight. Consequently, the pink and white areas are highest, and bluish and black areas the deepest. The storm is about 26,000 kilometers long and probably arose from instabilities in the planet's strongly east-west airflow. The artist's impression (*below*) exaggerates the vertical scale 1,000-fold.

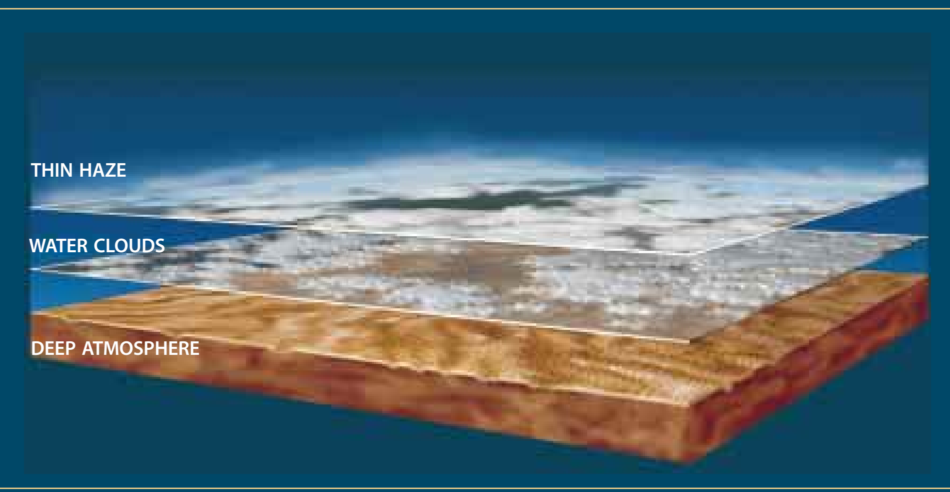


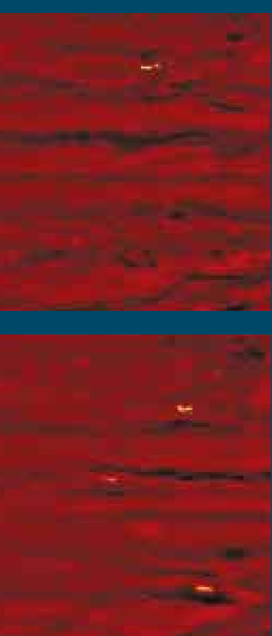
NASA/JET PROPULSION LABORATORY

DON DIXON

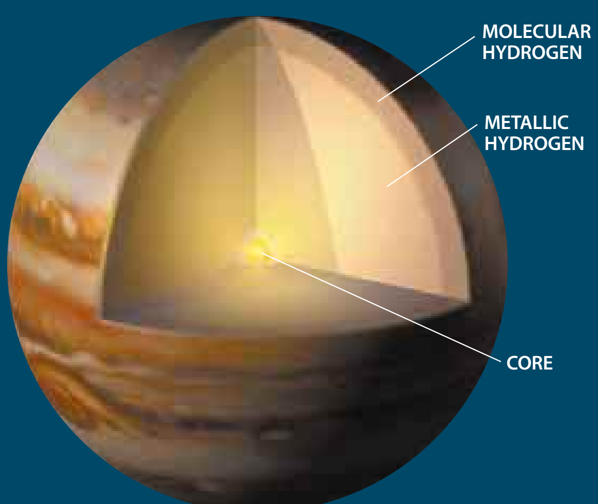
LIGHTNING FLASHES appear in these orbiter images of the night side of Jupiter. Moonlight from Io dimly illuminates the ammonia cloud deck. The flashes probably originate from water clouds 100 kilometers deeper. Lightning strikes at about the same rate as in thunderstorms on Earth but 1,000 times more brightly. Each image shows an area roughly 60,000 kilometers square.







INTERIOR OF JUPITER shows that the term "gas giant" is something of a misnomer. The bulk of the planet consists of hydrogen under such immense pressures that it has become liquid and metallic. Underneath it all is a core of rock around which the hydrogen accumulated.



When engineers received the "golden bit" confirming that the probe was still alive, cheers went up in the control room and the tension began to ease. But the team still had to wait out the next two hours for the second critical event: insertion of the companion spacecraft into orbit. To slow it from interplanetary cruise enough for Jupiter's gravity to capture it, engineers instructed the German-built main engine to fire for 45 minutes. Finally, word came through that this maneuver had succeeded. The orbiter had become the first known artificial satellite of the giant planet.

Since that day in December 1995, a mission that once seemed doomed has given researchers their first detailed view of the Jovian system, revealed only fleetingly in the Pioneer and Voyager flybys of the 1970s. The atmospheric probe penetrated the kaleidoscopic clouds and conducted the first in situ sampling of an outer planet's atmosphere, transmitting data for an hour before it was lost in the gaseous depths. The orbiter is still going strong. It has photographed and analyzed the planet, its rings and its diverse moons. Most famously, it has bolstered the case that an ocean of liquid water lurks inside Europa, one of the four natural satellites discovered by Galileo Galilei in 1610 [see "The Hidden Ocean of Europa," by Robert T. Pappalardo, James W. Head and Ronald Greeley; SCIENTIFIC AMERICAN, October 1999]. But the other large moons have revealed surprises of their own: beams of electrons that connect Io, the most volcanically tormented body in the solar system, to Jupiter; a magnetic field generated within Ganymede, the first such field ever discovered on a moon; and the subtle mysteries of Callisto, including signs that it, too, has an ocean.

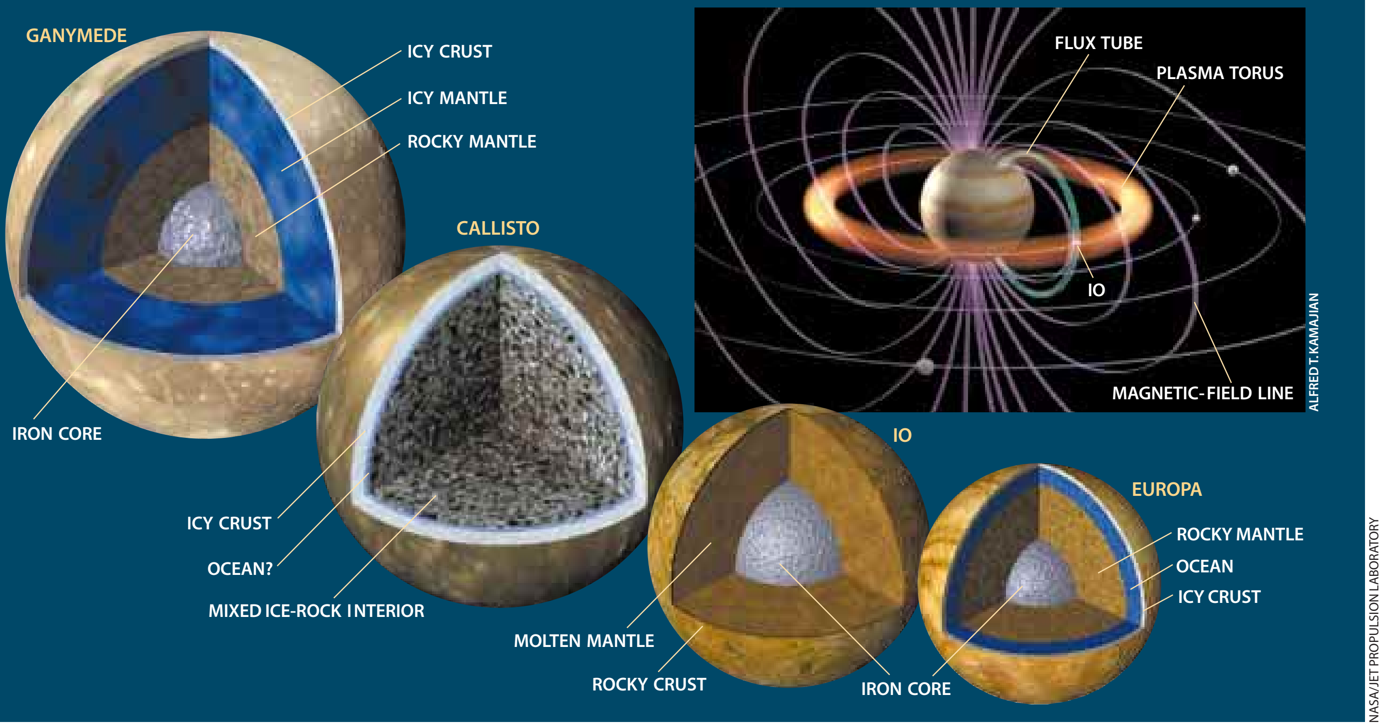
The Mother of All Downdrafts

According to modern theories of planet formation, Jupiter and the other giant planets emerged from the primordial solar nebula in two stages. First, icy planetesimals—essentially large comets that had condensed out of the cloud of gas and dust—clumped together. Then, as the protoplanet grew to a certain critical size, it swept up gas directly from the nebula. Jupiter thus started off with a sample of the raw material of the solar system, which had roughly the same composition as the early sun. Since then, the planet has been shaped by processes such as internal differentiation and the

The Interiors and Magnetic Fields of

Galilean Satellites

The four Galilean satellites of Jupiter do not really deserve to be called "moons." In many ways, they are planets in their own right. The inner two, Io and Europa, are about the size and density of Earth's moon. The outer two, Ganymede and Callisto, are about the size of Mercury but much less dense. Although Galileo did not land on or dig into them, it inferred their interior structure from their gravitational forces and magnetic fields. Of the four, only Callisto does not seem to have differentiated into distinct layers of metal, rock and water ice. Jupiter's electromagnetic fields interact with all four, but especially with Io (*diagram below*). The fields scoop up ionized gases from Io's volcanic eruptions, creating a torus of plasma. A flux tube between the planet and moons carries an electric current of five million amperes. (On this diagram, the planet and moons are not to scale.)



continuing infall of cometary material. Disentangling these processes was the main goal of the atmospheric probe.

Perhaps the most mysterious discovery by the probe involved the so-called condensable species, including elements such as nitrogen, sulfur, oxygen and carbon. Scientists have long known that Jupiter has about three times as much carbon (in the form of methane gas) as the sun. The other species (in the form of ammonia, ammonia sulfides and water) are thought to condense and form cloud layers at various depths. Impurities in the cloud droplets, possibly sulfur or phosphorus, give each layer a distinctive color. The probe was designed to descend below the lowest expected cloud deck, believed to be a water cloud at about 5 to 10 atmospheres of pressure—some 100 kilometers below the upper ammonia ice clouds. The expected weather report was windy, cloudy, hot and humid.

Yet the instruments saw almost no evidence for clouds, detecting only light hazes at a pressure level of 1.6 atmospheres. The water and sulfur abundances were low. The lightning detector—basically an AM radio that listened for bursts of static—registered only faint discharges. In short, the weather was clear and dry. So what had gone wrong with the prediction? One piece of the answer came quickly. Infrared images from Earth-based telescopes discovered that the probe had unwittingly hit a special type of atmospheric region known as a five-micron hot spot—a clearing where infrared radiation from lower, hotter levels leaks out. Jupiter has many such regions, and they continually change, so the probe could not be targeted to either hit or avoid them.

The luck (both good and bad) of descending in a hot spot did not entirely solve the mystery, however. Scientists had expected that even in these regions the gases at the depths the probe reached would match the average composition of the whole atmosphere. If so, Jupiter has an anomalously low amount of such elements as oxygen and sulfur. But no one has proposed a process that would eliminate these elements so efficiently. The other possibility is that the composition of the hot spot differs from the average, perhaps because of a massive downdraft of cold, dry gas from the upper atmosphere.

The latter theory has its own difficulties but currently seems the more likely interpretation. Just before the probe ceased transmitting, concentrations of water, ammonia and hydrogen sulfide were beginning to rise rapidly—just as if the probe was approaching the base of a downdraft. Orbiter images of another prominent hot spot show that winds converge on the center of the hot spot from all directions [*see illustration on page 42*]. The only place the gas can go is down. Orbiter spectra showed that the abundance of water and ammonia varies by a factor of 100 among different hot spots, supporting the idea that local meteorological conditions dictate the detailed composition of the atmosphere.

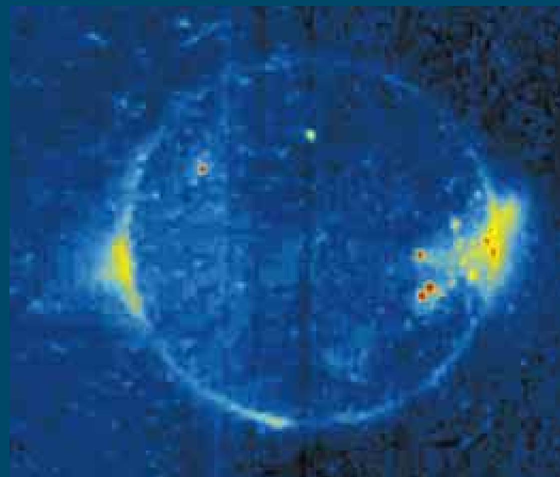
The one part of the weather prediction that proved correct was "windy." Jupiter's cloud bands are associated with high-velocity jet streams: westerlies and easterlies that blow steadily at several hundred kilometers per hour. On Earth the analogous winds die off near the surface. On Jupiter there is no surface; the wind profile depends on which energy source dominates the atmosphere. If a source of internal energy (such as slow contraction under the force of gravity) dominates, the winds should stay strong or increase with depth. The opposite is true if external energy (such as sunlight) is the main contributor. By tracking the probe's radio signal, scientists ascertained that winds at first increase rapidly with depth and then remain constant—indicating that Jupiter's atmosphere is driven by internal energy.

Onto Each Planet Some Rain Must Fall

Although the probe detected only weak hints of lightning, the orbiter saw bright flashes illuminating the clouds in what are obviously massive thunderstorms [*see illustration on page 42*]. Like Voyager, Galileo found that lightning was concentrated in just a few zones of latitude. These zones are regions of anticyclonic shear: the winds change speed abruptly going from north to south, creating turbulent, stormy conditions. As on Earth, lightning may occur in water clouds where partially frozen ice granules rise and fall in the turbulence, causing positive and negative charges to separate. How deep the lightning occurs can be estimated from the size of the illuminated spot on the clouds; the bigger the spot, the deeper the discharge. Galileo deduced that the lightning is indeed originating from layers in the atmosphere where water clouds are expected to form.

For all its pains, the probe descended less than 0.1 percent of the way to the center of the planet before succumbing to the high pressures and temperatures. Nevertheless, some of its measurements hint at what happens deeper down. The concentrations of noble gases—helium (the second most abundant element in Jupiter, after hydrogen), neon, argon, krypton and xenon—are particularly instructive. Because these gases do not react chemically with other elements, they are comparatively unambiguous tracers of physical conditions within the planet. So informative is the concentration of helium that the Galileo at-

The Infernal Moon
Io



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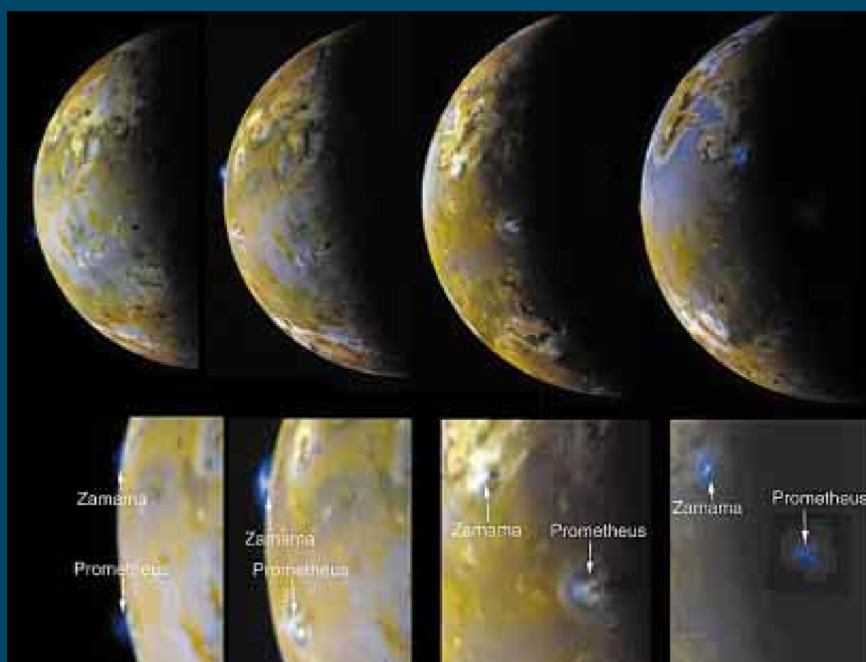
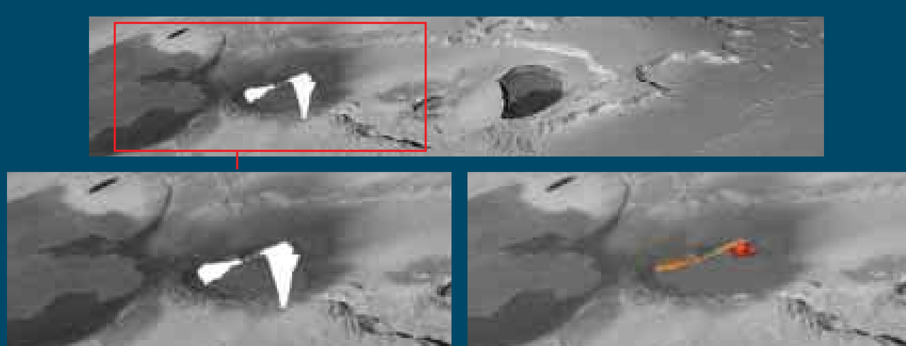
A yummy pizza color distinguished Io in the Voyager images two decades ago. Galileo's greater range of wavelengths permits even more spectacular false-color views. When the satellite is in Jupiter's shadow (*top*), lava flows become evident as small red and yellow spots. Volcanic plumes show up as glows along the edge; the one on the left is from the volcano Prometheus. A sequence of four enhanced-color images (*middle*) shows Prometheus and Zamama coming into view—first the plumes, then the volcanoes themselves, surrounded by rings of debris more than 100 kilometers in diameter. Last November, Galileo captured a huge volcanic complex in Io's northern climes (*bottom*). The image shows several craters and a massive curtain of fire. The fresh lava is glowing so brightly it overexposes the CCD camera.





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The Ice-Laced Moon of Ganymede

The largest satellite in the solar system is a strange quilt of dark and bright terrains. The dark regions, like Galileo Regio (*left*), are heavily cratered; the large crater in the foreground is 19 kilometers in diameter. Deep furrows may contain dust left behind after water ice sublimated away. The bright regions, like Uruk Sulcus (*below*), have fewer craters and more tectonic features such as grooves. This image depicts an area roughly 400 kilometers square. Some regions, like Tiamat Sulcus (*right*), shown here just after sunrise, contain both types of terrain.

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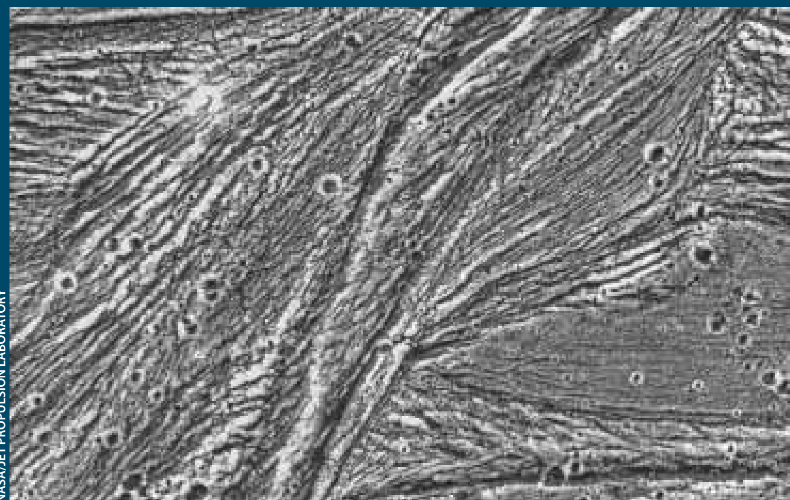

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mospheric probe carried an instrument dedicated solely to its measurement.

Infrared spectra obtained by Voyager suggested that Jupiter contains proportionately much less helium than the sun does, an indication that something must have drained this element from the upper atmosphere. Galileo, however, found that Jupiter has nearly the same helium content as the outer layers of the sun [*see table on page 42*]. This result still requires that some process remove helium from the Jovian atmosphere, because the outer layers of the sun have themselves lost helium. But that process must have started later in the planet's history than researchers had thought. Galileo also discovered that the concentration of neon is a tenth of its solar value.

Both these results support the once controversial hypothesis that the deep interior of Jupiter is deluged with helium rain. There helium becomes immisible in the hydrogen-rich atmosphere, which at high pressures—millions of times sea-level pressure on Earth—is perhaps better thought of as an ocean. Being heavier, the helium gradually settles toward the center of the planet. Under certain conditions, neon dissolves in the helium raindrops. Helium may also precipitate out on Saturn, whose helium depletion may be even more extreme.

After several years of analysis, researchers recently announced the abundance of the other noble gases. Argon, krypton and xenon are enriched compared with the solar composition by about the same factor as carbon and sulfur. That, too, is a mystery. The only way to trap the inferred quantities of these gases is to freeze them—which is not possible at Jupiter's current distance from the sun. Therefore, much of the material that makes up the planet must have come from colder, more distant regions. Jupiter itself may even have formed farther from the sun, then drifted inward [see "Migrating Planets," by Renu Malhotra; Scientific American, September 1999].

A final clue to Jovian history came from the measurement of deuterium, one of the heavy isotopes of hydrogen. The concentration is similar to that on the sun and is distinctly different from that of comets or of Earth's oceans. The finding suggests that comets have not had a major effect on the composition of Jupiter's atmosphere, despite the spectacular effects when they hit, as demonstrated during the Shoemaker-Levy 9 collisions in 1994.

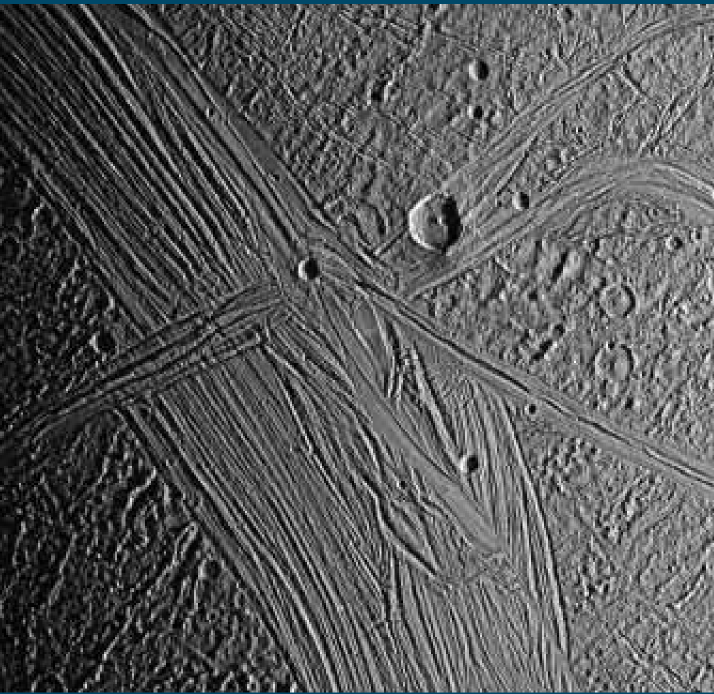
World of Fire

After the orbiter relayed the probe data to Earth, it commenced its tour of the Jovian system—to date, a total of 26 orbits of the planet, with multiple flybys of each of the four Galilean satellites. The limelight has been on Europa, whose surface geology and other features point to the existence of a liquid ocean beneath the ice sometime in Europa's history, probably in the geologically recent past. But the other moons have not been neglected.

The innermost Galilean satellite, Io, stole the show during the two Voyager encounters. The initial pictures from those spacecraft showed a remarkably young surface, the only one in the solar system with essentially no impact craters. Later, images taken for navigation purposes serendipitously caught immense eruptive plumes. Subsequent observations confirmed that Io is wracked by volcanic activity. The size of Earth's moon, it spews 100 times more lava than Earth does [see "Io," by Torrence V. Johnson and Laurence A. Soderblom; Scientific American, December 1983].

Galileo has spent less time looking at Io than at the other moons, primarily because of the danger to the spacecraft: Io lies deep in Jupiter's intense radiation belts. Galileo flew within 900 kilometers of Io's surface just before the orbit insertion in 1995 but did not revisit until last October, when the bulk of its mission had been completed and scientists felt free to take more risks. Although concerns about the jam-prone tape recorder forced cancellation of imaging and spectroscopy during the 1995 flyby, the particle detector and magnetometer remained active.

They found that the empty space around Io is anything but. It seethes with subatomic particles blasted out by volcanic eruptions and stirred up by Jupiter's magnetic field. Electron beams course down the field lines that connect



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Artist's impression of the surface

DON DAVIS

Io to Jupiter's atmosphere; dense, cold plasmas permeate the wake left behind Io by the magnetic field sweeping by. Whenever Io passed through Jupiter's shadow, Galileo saw the moon outlined by a thin ring of glowing gas, lit up by the impact of electrons from the Jovian magnetosphere. In short, Io is tightly linked to the giant planet by what amounts to the largest electric circuit in the solar system [*see illustration on page 44*].

For most of its mission Galileo studied the tortured surface of Io from a safe distance. Based on how brightly the volcanoes glow at different visible and near-infrared wavelengths, it inferred their temperature, a measurement critical to determining the composition of the lavas. Most volcanoes on Earth disgorge lava of basaltic composition—iron, magnesium and calcium silicates rich in the minerals olivine and pyroxene. Basaltic melts typically have temperatures ranging from 1,300 to 1,450 kelvins (1,050 to 1,200 degrees Celsius). In contrast, telescopic observations of Io several years ago suggested temperatures of 1,500 to 1,800 kelvins. These temperatures ruled out substances that melt at lower temperatures, such as liquid sulfur, which had been suggested previously as a dominant volcanic fluid on Io.

When Galileo's measurements came down, the enigma intensified. Lavas on the moon are actually 1,700 to 2,000 kelvins. Magma this hot has not been common on Earth for more than three billion years. Io may thus be giving scientists an unexpected glimpse into Earth's geologic youth, a time when its interior temperatures were higher and the composition of the upper mantle different from today's.

When Galileo finally returned to Io last fall, the mission team was uncertain whether the spacecraft would survive the radiation. On one of its passes, it autonomously aborted the data-taking sequence just four hours before reaching Io, and the team rebooted with only minutes to spare. Several instruments also suffered damage, but all continued to work and in the end returned spectacular data. Io's active volcanoes were finally captured up close and personal [*see illustration on page 45*].

In a Field of Its Own

One of Galileo's major discoveries was made during its very first orbital encounter—with Ganymede, Jupiter's largest moon. About half an hour before the spacecraft reached its closest approach, the radio-noise instrument, designed to record ambient electrical fields, began to go haywire. The relatively quiet background radio signals seen throughout most of the Jovian system changed abruptly to a complex, active radio spectrum. For 45 minutes the activity remained intense, and then it ceased as suddenly as it had begun. When the radio noise commenced, the magnetometer readings shot up fivefold.

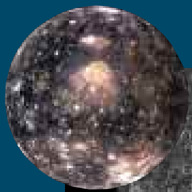
Plasma researchers had seen signatures of this sort before, when spacecraft carrying similar instruments entered and exited magnetospheres at Earth, Jupiter, Saturn, Uranus and Neptune. Two subsequent Ganymede flybys confirmed their suspicions: the moon is magnetized, generating a dipole field similar to those of these planets. No other satellite has such a field. Earth's moon and Mars may have had fields in the past, but currently they exhibit only limited patches of magnetic variation that represent magnetized rocks on the surface. Like a set of nested Russian dolls, Ganymede has a magnetosphere contained within Jupiter's huge magnetic domain, which in turn is embedded in the sun's.

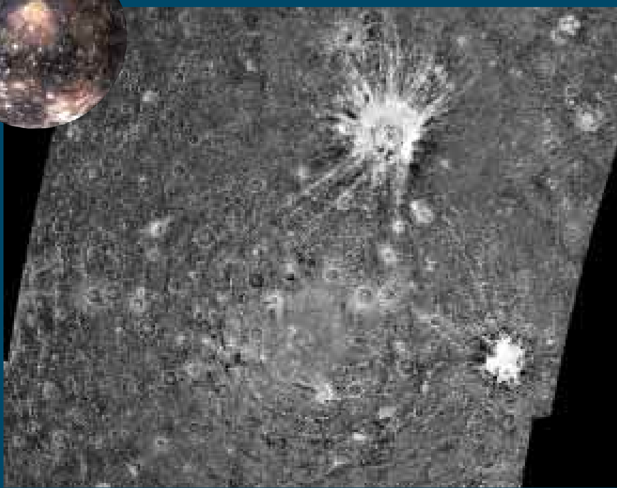
Tracking of the spacecraft signal allowed researchers to probe Ganymede's gravity field and therefore its internal structure. They concluded that it probably has a dense core about 1,500 kilometers in radius with a surrounding icy mantle 700 kilometers deep. Geochemical models suggest that the core consists of a sphere of iron or iron sulfide enveloped in rock. The inner metallic core could produce the dipolar magnetic field.

Yet theorists are not sure quite how. Although scientists compare planetary magnetic fields to bar magnets, the analogy can be misleading. Solid iron at the center of a planet or large moon would be too hot to retain a permanent magnetic field. Instead a magnetic field is thought to involve a convecting, conductive liquid. Models of Ganymede indicate that its interior can easily become

Pockmarked
Callisto

This most baffling of the Galilean satellites is densely packed with large craters, such as the massive, multiringed impact structure Asgard (*left*). Yet it is comparatively free of small craters, and those that do exist are fuzzy (*below* and *right*)—suggesting that dusty material has somehow flowed across the surface.





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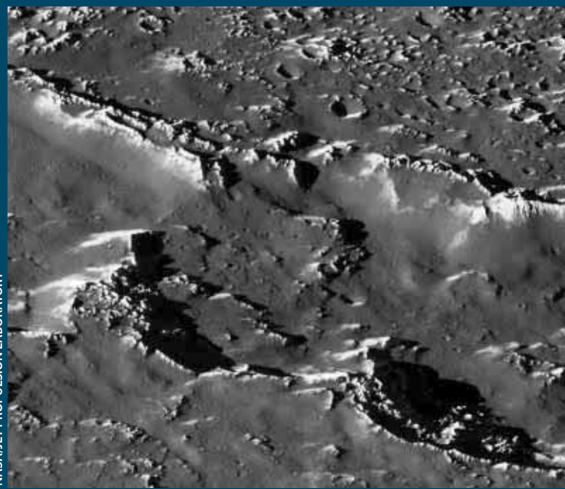

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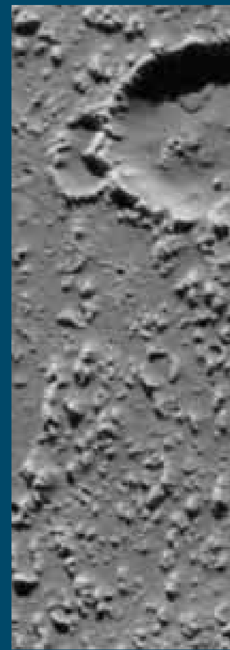


hot enough to melt iron or iron sulfide. But the same models show that convection will cease as the core gradually cools; the conditions required for convection should last only a billion years or so.

The answer may lie in the orbital resonance of the inner three Galilean satellites. Io goes around Jupiter precisely four times for each time Europa completes two circuits and Ganymede one. Like pushing a child's swing in time with its natural pendulum period, this congruence allows small forces to accumulate into large outcomes—in this case, distorting the orbits from their default circular shape into more oblong ellipses. The effect on the moons is profound. Because the distance between them and Jupiter is continuously changing, the influence of Jupiter's gravity waxes and wanes, stretching the moons by an ever varying amount. The process, known as tidal heating, drives the volcanism on Io and keeps Europa's putative ocean from freezing.

Researchers used to think that tidal heating was of little consequence for Ganymede, the outermost of these three moons. But now they realize that the orbits may have shifted over time. Consequently, the resonances may once have been stronger and Ganymede's orbit more perturbed than it is now. The immense fault systems that wind across the surface may record this earlier period of intense heating. If so, the moon is still cooling off, and its core can continue to generate a magnetic field.

Compared with flamboyant Europa, Io and Ganymede, the outermost Galilean satellite, Callisto, was always thought rather drab. In Voyager images it epitomized the traditional stereotype for icy satellites: an old, frozen, pockmarked mudball. But Galileo observations tell a different story.

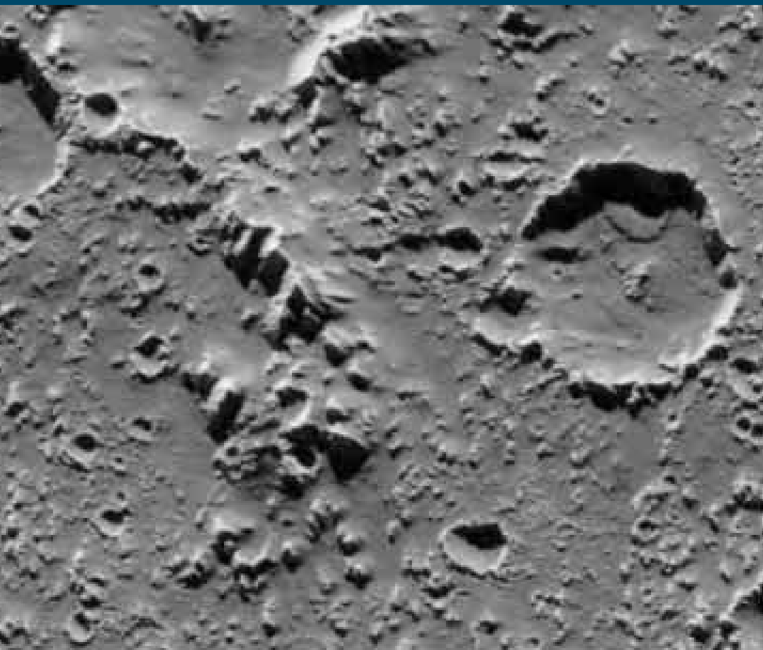
Old but Hardly Dull

Callisto is covered with large impact scars, ranging from craters kilometers in diameter to the so-called palimpsest named Valhalla, some 1,500 kilometers across. The surface is believed to date back more than four billion years to the rain of meteoritic and cometary debris left after the formation of the planets and satellites. In this sense, Callisto is indeed old. Seen close-up, however, Callisto's surface is blanketed by fine, dark debris. Small craters, which on most other bodies are produced in abundance, are largely absent. Surface features appear softened and eroded. Clearly, some young processes have been at work. Among the ideas proposed have been electrostatic levitation of fine dust, which would allow it to "flow" across the surface, and evaporation of ices from the surface, which would leave behind deposits of darker, less volatile material. So far none of the explanations is satisfying.

Intriguingly, near-infrared spectra show not only water ice and hydrated minerals, as expected, but also four unusual absorption features near a wavelength of four microns. One appears to be carbon dioxide trapped in the surface, perhaps as inclusions in icy particles or bubbles produced by radiation damage to the surface. Two other spectral features probably represent sulfur in the surface, which may originate in Io's volcanic eruptions. The fourth spectral feature is the strangest. Its wavelength corresponds to that absorbed by carbon-nitrogen bonds. In fact, laboratory spectra of complex organic molecules called tholins by the late Carl Sagan are similar. Tholins are thought to resemble organic material in the solar nebula; clouds of interstellar ice grains have comparable spectra. Taken together, the data provide the first direct evidence that icy satellites contain the carbon, nitrogen and sulfur compounds common in primitive meteorites and comets. These materials are also some of the most important for life.

The internal structure of Callisto shows the same paradoxical dichotomy between age and youth that the surface exhibits. Unlike the other Galilean satellites, Callisto seems more like a uniformly dense sphere, indicating that most of its rock and ice are mixed together. A core is ruled out. Therefore, the interior has never been heated strongly, either by radioactive decay or by tides. The moon does not participate in the orbital resonance that kneads the other Galilean satellites.

On the other hand, the moon is far from dead. As the Galileo magnetometer found, Callisto seems to perturb the surrounding Jovian magnetic field in a



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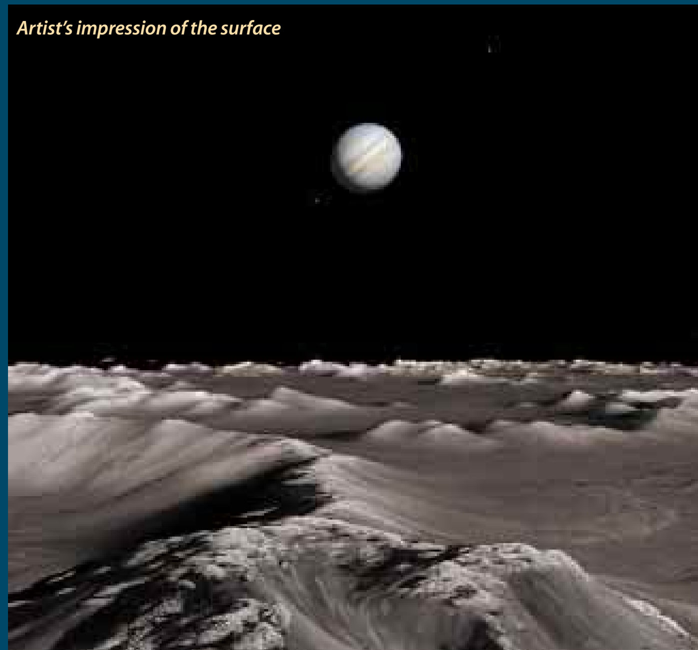

Artist's impression of the surface

DON DAVIS

peculiar pattern. This disturbance, unlike Ganymede's, resembles what is seen in classic physics experiments in which a hollow copper sphere is subjected to a changing magnetic field. In such an experiment, electric currents are set up in the conducting shell of the sphere, which in turn produces a magnetic field that exactly counters the imposed field. Callisto's field seems to be induced in much the same way.

But what could form the electrically conducting layer? Rock, ice and ionospheric particles are poor conductors. Researchers are left with a possibility that not long ago seemed outrageous: salty ocean water. Seawater is a weak conductor with the right properties to explain the readings. A global liquid layer some tens of kilometers thick could produce the observed signature. The combination of evidence for a comparatively undifferentiated interior and for a global ocean presents a severe challenge for theorists. Somehow Callisto must be hot enough to support an ocean but not so hot that light and heavy materials separate. The water layer might be sandwiched between a radioactively heated interior, where convection keeps the material mixed, and a thin icy shell, where a different convection cycle cools the ocean. So much for dull old Callisto.

Although much of Galileo's mission involved studies of the Galilean moons, the orbiter did not overlook the smaller members of Jupiter's family. Its camera captured each of the four inner, small moons—Metis, Adrastea, Amalthea and Thebe, in order of distance from Jupiter. A major finding was that these small moons are directly responsible for Jupiter's rings. A special series of pictures was taken while the spacecraft was within Jupiter's shadow, allowing the sun to backlight the tiny dust particles that make up the rings. These pictures not only show the main rings and the tenuous gossamer ring seen by Voyager in 1979, but also reveal for the first time the complex structure of the gossamer ring. It consists of multiple layers directly related to the orbits of Amalthea and Thebe. Thus, the rings are probably microscopic debris kicked off the moons by the impact of tiny metoroids. [*Editors' note: An upcoming article will examine the rings in greater detail.*]

The data gathered by Galileo have revolutionized scientists' view of Jupiter and its moons, which we have come to recognize as a kind of planetary system comparable in complexity to the solar system itself. The Voyager flybys provided the adrenaline rush of seeing worlds for the first time, but only an intensive investigation such as Galileo's could have revealed the nuances and the limitations of seemingly straightforward categories such as "thundercloud" and "icy satellite." Soon it will be Saturn's turn to enter this new phase of exploration. Another two-in-one spacecraft—Cassini-Huygens—arrives there in 2004. It, too, will probably raise more questions than it answers. SA

The Author

TORRENCE V. JOHNSON has an asteroid named after him: 2614 Torrence, a body about one kilometer in diameter. Working at the Jet Propulsion Laboratory in Pasadena, Calif., he has been the project scientist for Galileo since 1977—some three quarters of his career as a planetary scientist. He was a member of the imaging team for Voyager and is now on the imaging team for the Cassini mission to Saturn.

Further Information

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MELTING BELOW ZERO

New research shows how a layer of water on the surface of ice—even at temperatures well below freezing—can influence everything from the slipperiness of a skating rink to the electrification of thunderclouds

by John S. Wettlaufer and J. Greg Dash

The first weather report of the year warning of a cold snap sets homeowners to the task of insulating their most vulnerable water pipes. They know that preventing the water from freezing inside the pipes will avert damage that could happen as the water turns solid and expands. But what many people do not know is that they are also guarding against an even greater pressure generated because the surface of the ice remains liquid.

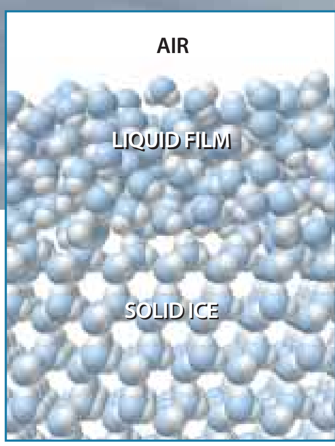
The freezing of water and the melting of ice are among the most common and dramatic examples of matter changing phases, yet basic aspects of how these transformations occur have long puzzled the physicists and chemists who study them. In the past 15 years, researchers have discovered some answers in a thin layer of water, only a few molecules thick.

This quasiliquid film, a natural state of solid ice formed by a process called surface melting, bears some structural characteristics of the solid below it but has the mobility of a fluid. Despite its microscopic size, this film plays a central role in the basic principles of melting and freezing—and in their many environmental consequences. Working both as a pathway for flowing water and as a carrier of electrical charge, this slick coating has the power to force boulders from the ground and to blast lightning bolts from the sky.

Snowballs and Ice Skates

On hearing the term "surface melting," one's first reaction might be to imagine how a solid melts from its surface inward as it is heated. A pat of butter on a stove or a lump of solder under a soldering iron begins to liquefy on its surface simply because the outside is hotter than the inside. But surface melting refers specifically to a less obvious effect: even if the solid is the same temperature inside and out, it develops a thin coating of its liquid phase at several tens of degrees Celsius below the overall melting point.

To understand the physics of surface melting, picture yourself deep inside an ice crystal, where the water molecules adopt a fixed and repeated pattern that builds a rigid lattice. As you move from the crystal's center to its surface, you periodically encounter water molecules, each one neatly coordi-



RICHARD HAMILTON SMITH *Corbis*; MICHAEL GOODMAN (*inset*)

FILMS OF WATER make ice surfaces slick for skaters, even at temperatures below freezing, because water molecules in the ice crystals lose their rigidity as they extend into the open air (*right*).

nated with its four nearest neighbors. As you approach the crystal's surface, however, the lattice becomes distorted as the outermost molecules reach out into the unstructured environment of the air around them. These surface molecules have the fewest chemical bonds holding them in place, and as a result they vibrate more violently as the temperature warms than do the molecules in the interior of the crystal. At a sufficiently high temperature—but still below the normal melting point—the molecules begin to flow in a liquidlike layer [*see illustration above*].

The idea that a thin film of liquid exists on the surface of ice is not a new one, but for many years people misunderstood its origin. Anyone who has ever taken sides in a snowball fight knows that to produce an effective projectile, the snow needs to be wet. Dry snow just does not stick together. And what about the futile attempt to manufacture a "sandball" at the beach? In the 1630s French scientist and philosopher René Descartes wrote down his observations of why ice sticks together. Some 200 years later musings over the same question challenged English physicist Michael Faraday to begin two decades of careful studies of snow and ice. "When wet snow is squeezed together, it freezes into a lump (with water between) and does not fall asunder as so much wetted sand or other kind of matter would do," Faraday wrote in the fall of 1842. Excerpts from Faraday's diary record the first investigation into what we know today as surface melting. It seemed to him that a thin layer of water coating the snowflakes must freeze to glue them together. This layer, he concluded, is a natural phenomenon of ice just below its melting point.

Faraday and fellow British physicist John Tyndall conducted independent experiments that proved—at least to them—that a liquid film exists on the surface of ice at equilibrium, but some powerful contemporaries were unconvinced. In 1849 James Thompson and his brother William Thompson (who later became Lord Kelvin) countered with a suggestion that the thin layer of water results only from the temporary lowering of the melting point, which occurs when another object in contact with the ice increases the pressure against it. Molecules are packed more tightly in water than in ice, so squeezing ice under the sharp blade of a skate, for instance, takes the solid a step closer to its liquid form.

This phenomenon, called pressure melting, became the accepted explanation for the slipperiness of ice and is still found in many textbooks today. A simple calculation, however, shows that pressure melting cannot explain this slick surface except at temperatures close to ice's normal melting point. A person gliding across a frozen lake on a conventional skate lowers the melting point of the ice by no more than a couple of degrees C. So if pressure melting were the only factor, a skate would slide only when the temperature hovered around freezing, a rather unsafe time to be out on an ice-covered lake anyway. To account for this discrepancy, Frank P. Bowden and T. P. Hughes of the University of Cambridge argued in 1939 that a different factor dominates at lower temperatures: friction between the ice and the skate blade creates enough heat to form a thin layer of water.

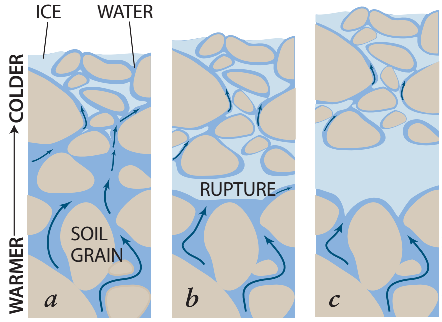
Both pressure melting and frictional heating have held scientists' attention for more than 100 years, but neither explains why, as any skater could tell you, it is so tricky to stand still on skates. Nor do these theories explain the underlying dynamics of frost heave or the electrification of thunderclouds, two important environmental effects of ice [*see box on next two pages*]. For complete answers, we turn back to Faraday's observations of surface melting, a phenomenon intrinsic to virtually all solids.

Wet Surfaces

Although physicists in addition to Faraday had predicted the existence of surface melting by the 1950s, no one actually observed the microscopic layer of liquid on a melting surface until the mid-1980s. In 1985 Joost M. W. Frenken and J. Friso van der Veen of the Institute for Atomic and Molecular Physics in Amsterdam fired beams of ions at a crystal of lead as they heated it to near the metal's melting

Environmental Effects of Surface Melting

COURTESY OF BERNARD HALLET *University of Washington*



MICHAEL GOODMAN

FROST HEAVE, which creates features such as these stone circles on the Arctic Ocean island of Spitsbergen, begins when moisture in the soil freezes. Warmer water travels upward along the liquid films that coat the ice (*a*). When the water pressure between the ice and soil grains overcomes that of the incoming water, the soil ruptures (*b*). Water rushes in and freezes, and the ground heaves in response (*c*).

THE HARD, COLD GROUND

After a fall freeze, farmers in rock-ribbed regions such as New Hampshire may awaken to an upheaval of their previously cleared fields: stones stand on pedestals of ice needles, and soil bulges up around larger rocks. This occurrence—called frost heave—ranges from an agricultural annoyance to an industrial nightmare. Despite its dramatic effects, frost heave owes its strength to microscopic liquid films on the surface of ice.

Frost heave begins when chilly air cools the soil and freezes some of the water near the top of the ground, but the real damage is wrought after this initial freeze. Molecular forces and impurities on the ice surfaces can prevent the moisture from freezing solid until the temperature drops several tens of degrees below zero Celsius. Until then, a microscopic film of water coats the ice crystals, which grow between the tiny fragments of rock and clay that make up the soil.

Water from deeper soils feeds the growth of the ice crystals. Warm water contains more free energy than cold water, and like all compounds, it wants to reach a state of lowest free energy. In freezing soils this tendency translates into what scientists call thermomolecular pressure: warm water is drawn toward areas where it can lose some of its energy by forming ice. Conveniently, the water has a built-in roadway—the liquid films on the ice surfaces.

Water continues to invade the spaces between the grains of icy soil until the buildup of water pressure there can counteract the pressure of the incoming water. This force between the ice and soil grains can grow to about 160 pounds per square inch for every degree below zero C, until the ice freezes completely. (For comparison, a service station's typical hydraulic lift needs only 21 pounds per square inch to raise a 3,000-pound car.) Most often, the soil ruptures underground long before this pressure is reached. Water then flows into the void, where it freezes into a solid layer of ice. The ice layer widens as more water flows in and freezes, forcing the ground above to heave.

In a recent study at the University of Washington, Larry A. Wilen, now at Ohio University, designed a simple apparatus that enabled him to make the first direct measurement of a microscopic equivalent of frost heave. Wilen fashioned a dime-shaped chamber, which enclosed an ice crystal encircled by water. A glass plate served as one face of the chamber, and a sheet of plastic formed the other. Between zero and –1 degree C, a film of water formed where the ice touched the plastic.

Wilen cooled the disk's surface so that its center was the coldest. The water at the disk's warmer edge, driven by the resulting thermomolecular pressure, flowed toward the center of the ice crystal along the liquid film. Some of the water froze along this path and raised the plastic cover, just as growing layers of ice underground pushed soil apart. With Grae Worster of the University of Cambridge, we have since developed a theory explaining the microscopic motion of this liquid film that drives frost heave.

ELECTRIFYING COLLISIONS

On a hot summer day we may dream of cooler times—and of ice, perhaps. And then, with a crash of lightning, ice falls as a downpour of hailstones. Ice is also there in the thunderhead, actively involved in the genera-

point, 328 degrees C. From the way the ions bounced back, the two researchers deduced that the rigid lattice of atoms at the crystal's surface became increasingly disordered—and began to resemble atoms in a fluid—at only 318 degrees C. The film thickened gradually as the temperature continued to rise, eventually melting the crystal from the surface inward. In 1986 Da-Ming Zhu, then a doctoral student at the University of Washington, and one of us (Dash) found that thin films of argon and neon undergo gradual phase changes below their normal melting points. Since then, researchers have shown that virtually all solids undergo surface melting.

So it is with ice. Several investigators have monitored the surface melting of ice in the laboratory, but their conclusions about the thickness of the film and its dependence on temperature are not always consistent. The variability may stem partly from difficulties interpreting results of multiple techniques. Optical techniques, for example, record the density difference between the liquid film and the solid ice by the way each reflects light. Another method examines the structure of the crystal surface by measuring the way it scatters x-rays.

An additional factor that can widen the gap between the results of experiments using the same instrument is the great sensitivity of the liquid film to impurities dissolved in the water. Airborne impurities, most notably salts and carbon dioxide, can make their way into the instrument and build up on ice surfaces during freezing. We are just beginning to explore their influence on surface melting, but recent theoretical work by one of us (Wettlaufer) suggests that impurities enhance surface tion of lightning. One of the most spectacular phenomena in everyday life, lightning was once explained as the thunderbolts of angry gods; in a later age it stimulated research on the basic nature of electricity. As it turns out, the microphysics of ice holds the key to how charge develops in clouds. The electrification involves a liquid film—only a few molecules thick—that coats the surface of ice crystals blowing through the clouds.

Lightning typically originates from the base of the cloud, where it is cold enough to freeze droplets of moisture. As these tiny ice crystals rise in updrafts, they bump into large clumps of hail falling to the ground. The smaller ice crystals tend to ricochet upward from the collision with a positive charge, leaving an equal negative charge on the falling hail. As a result, the cloud builds up electrical charge—positive charges near the top of the cloud and negative charges near the bottom.

Researchers gathered this information from observations and laboratory simulations, but they have struggled to account for the amount or sign of the clouds' electrical charge. In 1984 Greg J. Turner and C. David Stow of the University of Auckland in New Zealand proposed that the thin films of water that coat the surfaces of the ice crystals and the hailstones might be involved in the charging process. Five years later our University of Washington colleague Marcia Baker and one of us (Dash) explained how this might work: electrical charge is carried along with water that moves from the hailstones to the ice crystals when they collide.

Brian Mason tested this theory in our laboratory as part of his doctoral research, which he completed in 1998. Mason weighed grains of ice before and after a collision using two quartz-crystal microbalances, which can detect changes in mass on the order of a few ten-billionths of a gram—sensitive enough to detect the minuscule mass of a few layers of water molecules. He also measured the electric currents that flowed during the collisions to determine whether charge moved with mass.

As Baker and Dash's theory had predicted, a transfer of mass was always associated with the movement of charge. The growing ice crystal—which gained a layer of water only hundreds of molecules thick over an area of one hundredth of a square millimeter—adopted a positive charge after the collision.

FRANK A. CARA *Bruce Coleman Inc.*

LIGHTNING typically originates from the base of thunderclouds, where falling hailstones accumulate a negative charge during collisions with ice crystals blowing in updrafts (*inset*).

In a surprising and significant result, Mason found that the amount of mass transferred was far greater than the basic theory of surface melting, which depends on temperature and the size of the crystal, could explain. This discrepancy was one of the essential clues that led us to develop a more rigorous model of the collisions that electrify clouds. At the heart of our theory is a mechanism that increases the tendency of ice to liquefy even below its melting point: a forceful collision can create enough damage in the ice's solid molecular lattice to melt additional liquid, even at 10 or more degrees below its melting point. Together with impurities, such as carbon dioxide, that are commonly present on ice, collisions lead to an increasingly thick film of water. The thickness of the film is important because it liberates more liquid mass and charge that can then move from one icy surface to another.

The formation of a liquid after such an impact also liberates negatively charged ions that had accumulated near the surface of the ice crystal as it grew. During a collision, ice crystals and hailstones share a melted layer, and the growing crystals lose some of their negative ions. That is how we suspect that hailstones falling through the base of the cloud gather the negative charge from which lightning originates.

Further experiments and calculations will test these new ideas, but there seems little doubt that the charging mechanism that leads to spectacular lightning displays and the forces that drive frost heave lie in a layer of water only a few molecules thick. *—J.S.W. and J.G.D.*

melting. As it turns out, the solid ice efficiently rejects impurities that build up in the liquid films because they do not fit into its crystal lattice. Dissolved salts, for example, can thereby increase the thickness of the film by lowering both the melting point of the ice and the free energy of the liquid.

More than 150 years after Faraday's first observations of thin liquid layers on the surface of ice, we are only starting to tease out the underlying physical mechanisms responsible for its slipperiness, adhesive properties and outright destructive power. Many questions remain. What we do know is that a better grasp of the microphysics of ice will lead us closer to understanding its environmental effects. Delving into the molecular origins of frost heave and cloud electrification are but two possible avenues of research. SA

The Authors

JOHN S. WETTLAUFER and J. GREG DASH, both physicists at the University of Washington, collaborate frequently. Their joint research has focused on how microscopic properties of ice surfaces and phase transitions drive large-scale phenomena in the environment.

Further Information

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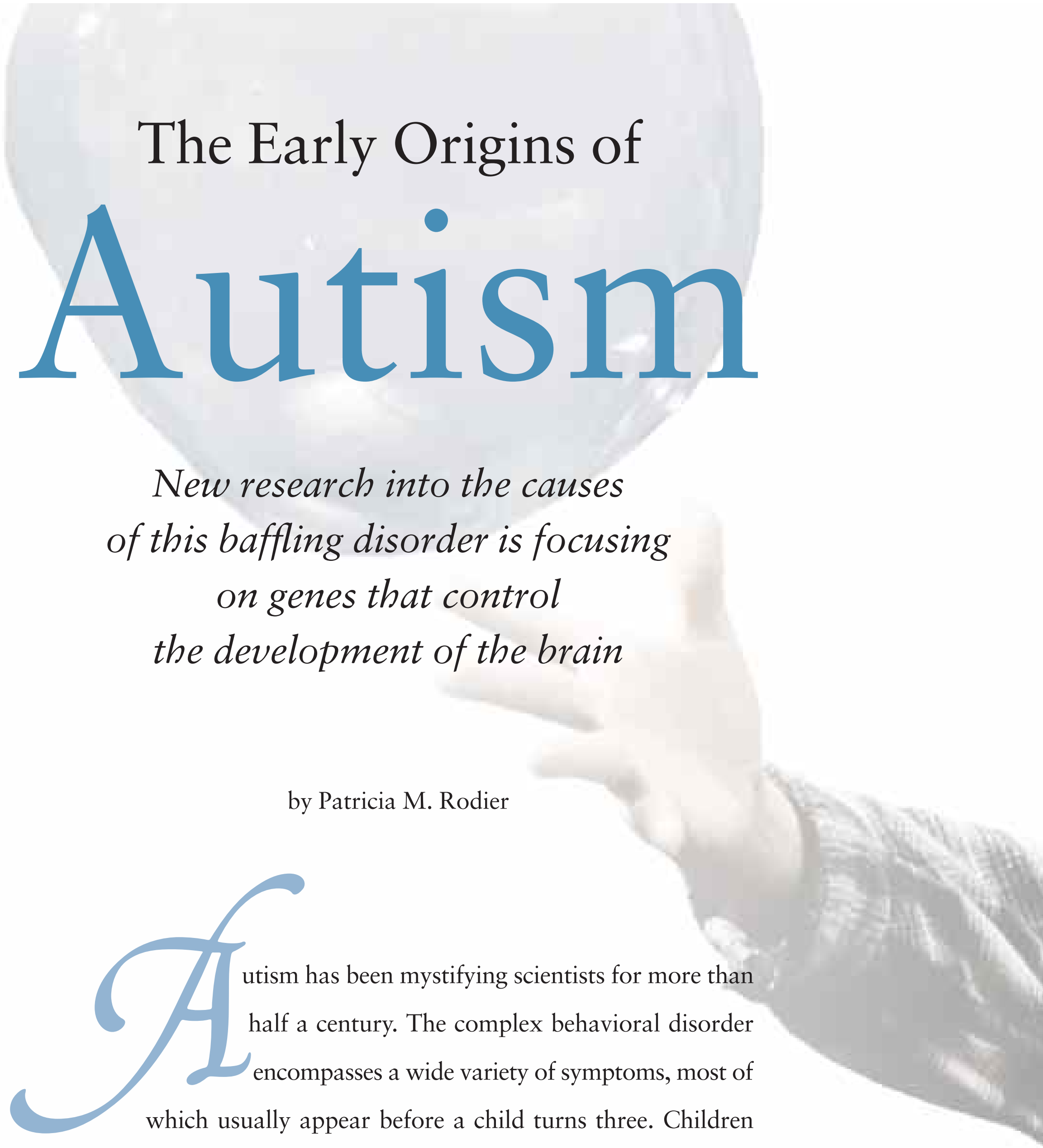
For additional references, visit Furio Ercolessi's Surface Physics Web site at http://www.sissa.it/cm/sp/course/refs.html



The Early Origins of Autism

New research into the causes of this baffling disorder is focusing on genes that control the development of the brain

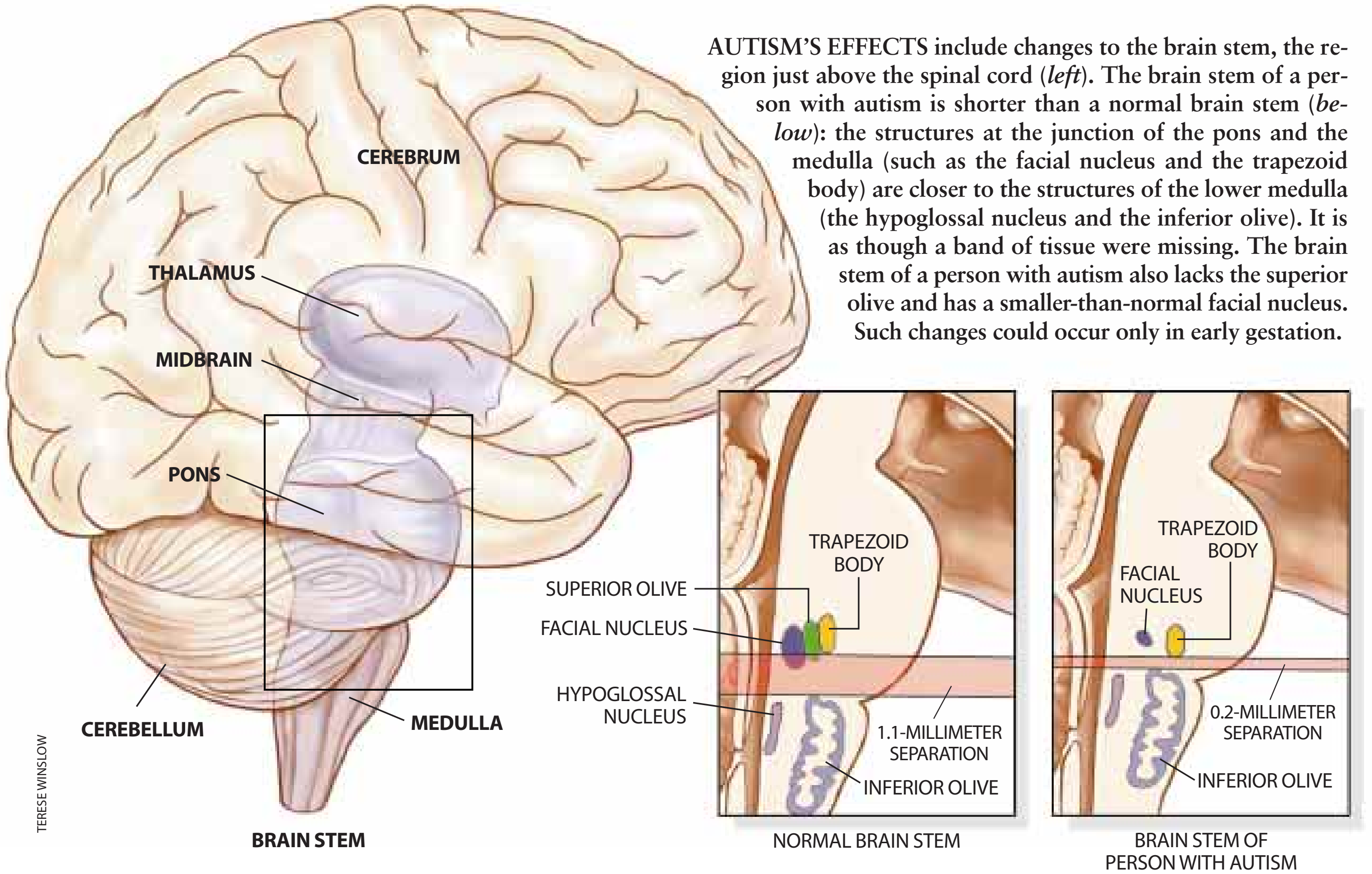
by Patricia M. Rodier

Autism has been mystifying scientists for more than half a century. The complex behavioral disorder encompasses a wide variety of symptoms, most of which usually appear before a child turns three. Children with autism are unable to interpret the emotional states of others, failing to recognize anger, sorrow or manipulative intent. Their language skills are often limited, and they find it difficult to initiate or sustain conversations. They also frequently exhibit an intense preoccupation with a single subject, activity or gesture.

These behaviors can be incredibly debilitating. How can you be included in a typical classroom if you can't be dissuaded from banging your head on your desk? How can you make friends if your overriding interest is in calendars? When children with autism also suffer from mental retardation—as most of them do—the prognosis is even worse. Intensive behavioral therapy improves the outcome for many patients, but their symptoms can make it impossible for them to live independently, even if they have normal IQs.

SEVEN-YEAR-OLD WITH AUTISM reaches for a soap bubble during playtime at the Eden Institute, a school for children with autism in Princeton, N.J.

JUSTINE PARSONS



AUTISM'S EFFECTS include changes to the brain stem, the region just above the spinal cord (*left*). The brain stem of a person with autism is shorter than a normal brain stem (*below*): the structures at the junction of the pons and the medulla (such as the facial nucleus and the trapezoid body) are closer to the structures of the lower medulla (the hypoglossal nucleus and the inferior olive). It is as though a band of tissue were missing. The brain stem of a person with autism also lacks the superior olive and has a smaller-than-normal facial nucleus. Such changes could occur only in early gestation.

I became involved in the search for autism's causes relatively recently—and almost by accident. As an embryologist, I previously focused on various birth defects of the brain. In 1994 I attended a remarkable presentation at a scientific conference on research into birth defects. Two pediatric ophthalmologists, Marilyn T. Miller of the University of Illinois at Chicago and Kerstin Strömland of Göteborg University in Sweden, described a surprising outcome from a study investigating eye motility problems in victims of thalidomide, the morning-sickness drug that caused an epidemic of birth defects in the 1960s. The study's subjects were adults who had been exposed to the drug while still in the womb. After examining these people, Miller and Strömland made an observation that had somehow eluded previous researchers: about 5 percent of the thalidomide victims had autism, which is about 30 times higher than the rate among the general population.

When I heard these results, I felt a shock of recognition, a feeling so powerful that I actually became dizzy and began to hyperventilate. In the effort to identify autism's causes, researchers had long sought to pinpoint exactly when the disorder begins. Previous speculation had focused on late gestation or early postnatal life as the time of origin, but there was no evidence to back up either hypothesis. The connection with thalidomide suddenly threw a brilliant new light on the subject. It suggested that autism originates in the early weeks of pregnancy, when the embryo's brain and the rest of its nervous system are just beginning to develop. Indeed, Miller and Strömland's work convinced me that the mystery of autism could soon be solved.

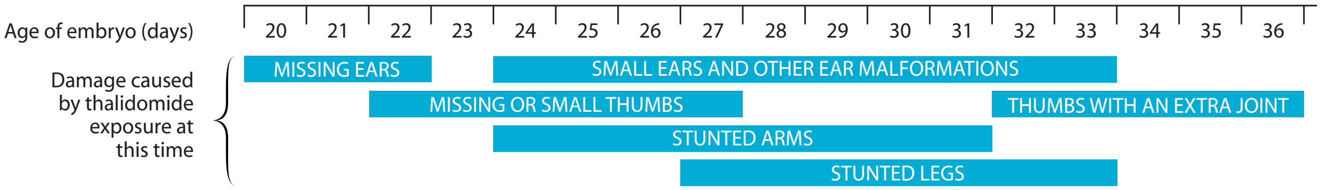
At least 16 of every 10,000 babies are born with autism or one of its related disorders.

Genetic Factors

At least 16 of every 10,000 babies is born with autism or one of its related disorders [*see box on page 60*]. Since autism was first identified in 1943, scientists have made great strides in describing its symptoms. The biological basis for autism, however, has been elusive—an unfortunate circumstance, because such an understanding could enable researchers to identify the leading risk factors for autism and possibly to design new treatments for the condition.

By examining the inheritance of the disorder, researchers have shown that autism runs in families, though not in a clear-cut way. Siblings of people with autism have a 3 to 8 percent chance of being diagnosed with the same disorder. This is much greater than the 0.16 percent risk in the general population but much less than the 50 percent chance that would characterize a genetic disease caused by a single dominant mutation (in which one faulty gene inherited from one parent is sufficient to cause the disorder) or the 25 percent chance that would characterize a single recessive mutation (in which a copy of the faulty gene must be inherited from each parent). The results fit best with models in which variants of several genes contribute to the outcome. To complicate matters further, relatives of people with autism may fail to meet all the criteria for the disorder but still have some of its symptoms. Although these relatives may have some of the gene variants linked to autism—what-

Thalidomide Timeline



JOHNNY JOHNSON

PETIT FORMAT/NESTLE/SCIENCE SOURCE *Photo Researchers, Inc.*

BIRTH DEFECTS caused by thalidomide vary depending on when the mother was exposed to the drug (*above*). A 1994 study showed that thalidomide victims with autism had ear anomalies and normal limbs, suggesting that the drug triggered the disorder 20 to 24 days after conception, when the embryo's nervous system is starting to form (*right*).

ever they may be—for some reason the genetic factors are not fully expressed in these individuals.

Studies of twins in the U.K. confirm that autism has a heritable component but suggest that environmental influences play a role as well. For example, if genetic factors alone were involved, monozygotic (identical) twins, who share the same genes, should have a 100 percent chance of sharing the same diagnosis. Instead, when one twin has autism, the second twin has only a 60 percent chance of being diagnosed with the same disorder. That twin also has an 86 percent chance of having some of autism's symptoms. These figures indicate that other factors must modify the genetic predisposition to the disorder.

The Embryology of Autism

Several environmental risk factors are already known. In utero exposure to rubella (German measles) or to birth defect–causing substances such as ethanol and valproic acid increases the chances that autism will develop. People with certain genetic diseases, such as phenylketonuria and tuberous sclerosis, also have a greater chance of developing autism. None of these factors, however, is present frequently enough to be responsible for many cases. Furthermore, most exposures to diseases or hazardous substances would be likely to affect both members of a pair of twins rather than just one. Some of the environmental influences must be more subtle than those identified so far. Researchers do not know how the multiple factors combine to make some people display symptoms while allowing others to escape them. This variation makes the search for autism's causes especially difficult.

In their 1994 study Miller and Strömland added another environmental contributor to autism: thalidomide exposure in utero. All their subjects—Swedish adults born in the late 1950s and early 1960s—exhibited some of the malformations for which thalidomide is infamous: stunted arms and legs, misshapen or missing ears and thumbs, and neurological dysfunctions of the eye and facial muscles. Because scientists know which organs of the embryo are developing at each stage of pregnancy, they can pinpoint the exact days when a malformation can be induced: the thumb is affected as early as day 22 after conception, the ears from days 20 to 33, and the arms and legs from days 25 to 35. What made the new study so exciting for me was Miller and Strömland's discovery that most of the thalidomide victims with autism had anomalies in the external part of their ears but no malformations of the arms or legs. This pattern indicated that the subjects had been injured very early in gestation—20 to 24 days after conception—before many women even know they are pregnant.

For embryologists, nothing tells us so much about *what* happened to an embryo as knowing *when* it happened. In the case of thalidomide-induced autism, the critical period is much earlier than many investigators would have guessed. Very few neurons form as early as the fourth week of gestation, and most are motor neurons of the cranial nerves, the ones that operate the muscles of the eyes, ears, face, jaw, throat and tongue. The cell bodies of these neurons are located in the brain stem, the region between the spinal cord and the rest of the brain. Because these motor neurons develop at the same time as the external ears, one might predict that the thalidomide victims with autism would also suffer from dysfunctions of the cranial nerves. Miller and Strömland confirmed this prediction—they found that all the subjects with autism had abnormalities of eye movement or facial expression, or both.

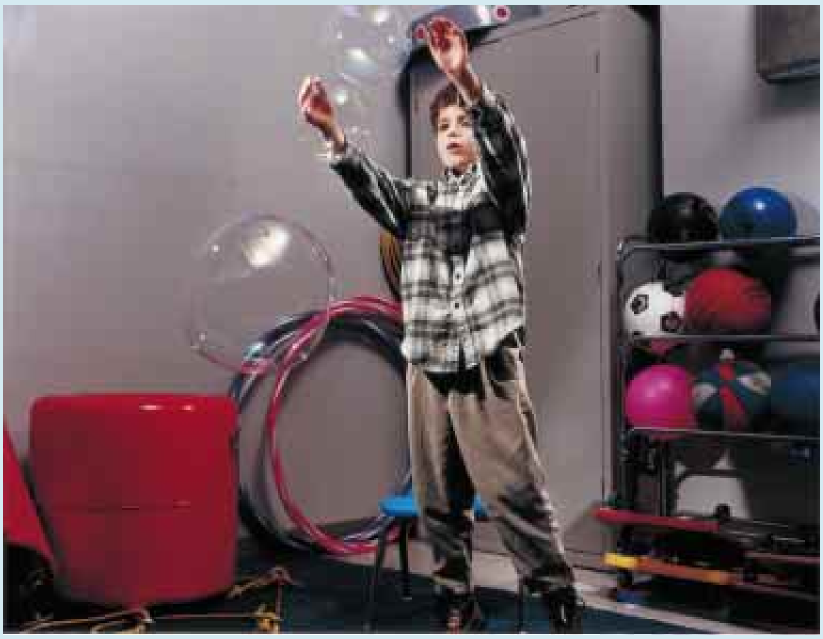
COURTESY OF SUSAN L. HYMAN

CHILD WITH AUTISM is normal in appearance, at least to the untrained eye. But he has a few physical anomalies characteristic of the disorder. The corners of his mouth are low compared with the center of his upper lip, and the tops of his ears flop over (*left*). His ears are a bit lower than normal and have an almost square shape (*right*).

The Spectrum of Autism Disorders

A diagnosis of autism requires that the patient exhibit abnormal behaviors in three categories [*see list at right*] and have especially notable deficits in the category of social interaction. In addition, clinicians have identified several related disorders that share some of the behavioral features of autism but have different emphases or additional symptoms. For example, Pervasive Development Disorder, Not Otherwise Specified (PDD-NOS) denotes patients who miss fulfilling the autism criteria in one of the three categories. As is true of autism, PDD-NOS includes patients with the whole range of IQs. Asperger syndrome is used to describe patients with normal IQs and no evidence of language delay. Two much rarer diagnoses are Childhood Disintegrative Disorder, in which normal early development is followed by regression to severe disability, and Rett syndrome, a progressive neurological disorder that occurs only in females.

Although many scientists have long known that autism is an inherited disease, recent family studies by Peter Szatmari's group at McMaster University in Ontario suggest that it is the spectrum of symptoms that runs in families rather than a single diagnosis. For example, a child with autism may have a brother with Asperger syndrome, or a woman with autism may have a nephew with PDD-NOS. These family studies strongly suggest that at least three of the diagnoses—autism, PDD-NOS and Asperger syndrome—arise from some of the same inherited factors. *—P.M.R.*



PHOTOGRAPHS BY JUSTINE PARSONS; SOURCE FOR "DIAGNOSTIC CATEGORIES": *DIAGNOSTIC AND STATISTICAL MANUAL OF MENTAL DISORDERS (DSM-IV)*

The next logical question was, "Are the cases of autism after thalidomide exposure similar to cases of unknown cause, or are they different?" Aside from their behavioral symptoms, people with autism have often been described not only as normal in appearance but as unusually attractive. They are certainly normal in stature, with normal-to-large heads. The few studies that have tested nonbehavioral features of people with autism, however, have concluded that there are indeed minor physical and neurological anomalies in many cases, and they are the same ones noted in thalidomide-induced autism. For example, minor malformations of the external ears—notably posterior rotation, in which the top of the ear is tilted backward more than 15 degrees—are more common in children with autism than in typically developing children, children with mental retardation or siblings of children with autism. Dysfunctions of eye movement had been associated with autism before the thalidomide study, and lack of facial expression is one of the behaviors used to diagnose the condition.

The Neurobiology of Autism

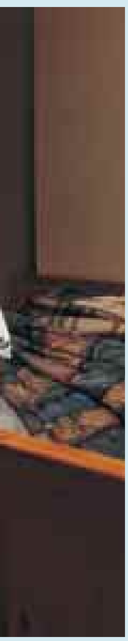
Is it possible that all the symptoms of autism arise from changes in the function of the cranial nerves? Probably not. It is more likely that the nerve dysfunctions in people with autism reflect an early brain injury that not only affects the cranial nerves but also has secondary effects on later brain development. That is, the injury to the brain stem might somehow interfere with the proper development or wiring of other brain regions, including those involved in higher-level functions such as speech, resulting in the behavioral symptoms of autism. Or perhaps the ear malformations and cranial nerve dysfunctions are only side effects of an injury that we don't understand. Whatever the true situation may be, the anomalies in patients with autism of unknown cause were much the same as the anomalies in the thalidomide victims with autism. The conclusion was clear: many cases of autism, if not all, are initiated very early in gestation.

Diagnostic Categories

Impairment of Social Interaction: Failure to use eye contact, facial expression or gestures to regulate social interaction; failure to seek comfort; failure to develop relationships with peers.

Impairment of Communication: Failure to use spoken language, without compensating by gesture; deficit in initiating or sustaining a conversation, despite adequate speech; aberrant language (for example, repeating a question instead of replying).

Restricted and Repetitive Interests and Behaviors: Abnormally intense preoccupation with one subject or activity; distress over change; insistence on routines or rituals with no purpose; repetitive movements, such as hand flapping.



BEHAVIORAL THERAPY for children with autism can help them lead happier lives as adults. Instructors at the Eden Institute school carefully evaluate the symptoms of each child to draw up an appropriate intervention plan. They often engage the children in stimulating play activities (*far left*). The institute also provides supervised housing for adults with autism (*left*). The 37-year-old man pictured here used videocassette spools to make the curtain behind his bed; his intense interest in these objects is a characteristic behavior of autism.

The region of the brain implicated by the thalidomide study—the brain stem—is one that has rarely been considered in studies of autism or in studies of other kinds of congenital brain damage, for that matter. On a simplistic level, neurobiologists associate the brain stem with the most basic functions: breathing, eating, balance, motor coordination and so forth. Many of the behaviors disturbed in autism, such as language, planning and interpretation of social cues, are believed to be controlled by higher-level regions of the brain, such as the cerebral cortex and the hippocampus in the forebrain.

Yet some symptoms common in autism—lack of facial expression, hypersensitivity to touch and sound, and sleep disturbances—do sound like ones more likely to originate in the brain regions associated with basic functions. Furthermore, the most consistently observed abnormality in the brains of people with autism is not a change in the forebrain but a reduction in the number of neurons in the cerebellum, a large processing center of the hindbrain that has long been known to have critical functions in the control of muscle movement.

One reason for scientists' confusion about the brain regions involved in autism may be that our assumptions about where functions are controlled are shaky. For example, the laboratory group led by Eric Courchesne of the University of California at San Diego has shown that parts of the cerebellum are activated during certain tasks requiring high-level cognitive processing. Another difficulty is that the symptoms of autism are so complex. If simpler behavioral abnormalities could be shown to be diagnostic of the disorder, researchers might have a better chance of identifying their source in the nervous system [*see box on next page*].

In 1995 our research team had the opportunity to follow up on the thalidomide study by examining the brain stem of a person with autism. The tissue samples came from the autopsy of a young woman who had suffered from autism of unknown cause; she had died in the 1970s, but fortunately the samples of her brain tissue had been preserved. When we examined the woman's brain stem, we were struck by the near absence of two structures: the facial nucleus, which controls the muscles of facial expression, and the superior olive, which is a relay station for auditory information. Both structures arise from the same segment of the embryo's neural tube, the organ that develops into the central nervous system. Counts of the facial neurons in the woman's brain showed only about 400 cells, whereas counts of facial neurons in a control brain showed 9,000.

Overall, the woman's brain was normal in size; in fact, it was slightly heavier than the average brain. I hypothesized that the brain stem was lacking only the specific neurons already identified—those in the facial nucleus and the superior olive—and to test that idea I decided to measure the distances between a number of neuroanatomical landmarks. I was surprised to discover that my hypothesis was absolutely wrong. Although the side-to-side measures were indeed normal, the front-to-back measures were astonishingly reduced in the brain stem of the woman with autism. It was as though a band of tissue had been cut out of the brain stem, and the two remaining pieces had been knit back together with no seam where the tissue was missing.

For the second time in my life, I felt a powerful shock of recognition. I heard a roaring in my ears, my vision dimmed, and I felt as though my head might explode. The shock was not generated by the unexpected result but by the realization that I had seen this pattern of shortening before, in a paper that showed pictures of abnormal mouse brains.

Many cases of autism, if not all, are initiated very early in gestation.

When I retrieved the article from the stacks of papers on my office floor, I found that the correspondence between the brain I had been studying and the mouse brains described in the article was even more striking than I had remembered. Both cases exhibited shortening of the brain stem, a smaller-than-normal facial nucleus and the absence of a superior olive. Additional features of the mice were clearly related to other anomalies associated with autism: they had ear malformations and lacked one of the brain structures controlling eye movement.

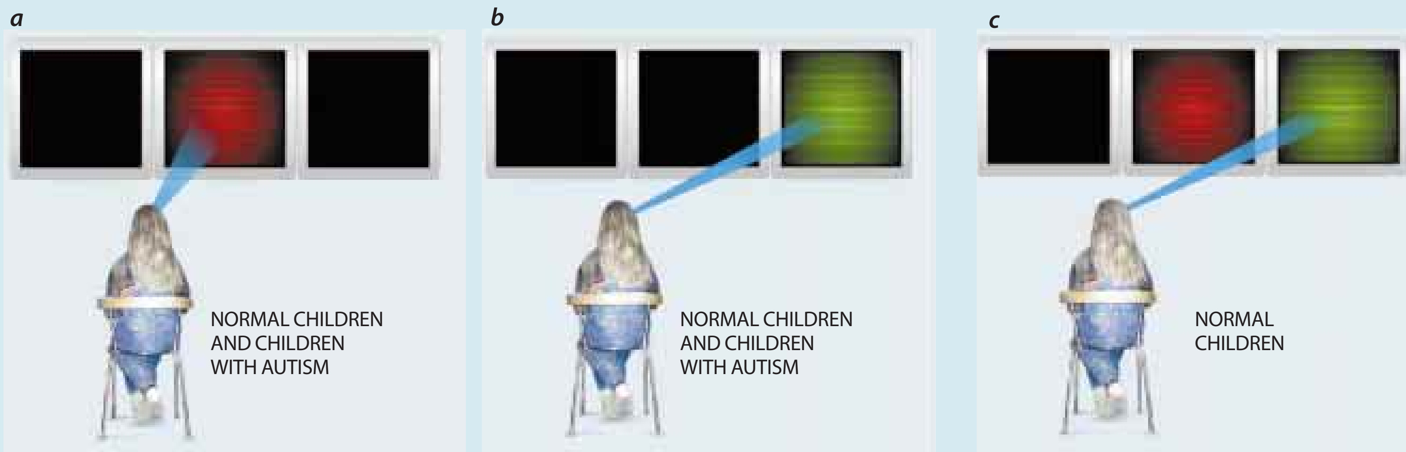
What had altered the brains of these mice? It was not exposure to thalidomide or any of the other environmental factors associated with autism but the elimination of the function of a gene. These were transgenic "knockout" mice, engineered to lack the expression of the gene known as *Hoxa1* so that researchers could study the gene's role in early development. The obvious question was, "Could this be one of the genes involved in autism?"

The literature supported the idea that *Hoxa1* was an excellent candidate for autism research. The studies of knockout mice showed that *Hoxa1* plays a central role in development of the brain stem. Groups in Salt Lake City and

A Simpler Symptom of Autism

Scientists at York University and the Hospital for Sick Children in Toronto have recently identified an autism-related behavior that is much simpler than the array of behaviors that have traditionally been used to diagnose the condition. Susan Bryson and her doctoral student Reginald Landry have found that children with autism respond abnormally to a task involving their reactions to visual stimuli. Because this mental activity is probably mediated by a primitive part of the brain—most likely the brain stem or the cerebellum, or both—the discovery has important implications for the neurobiology of autism. Bryson and Landry's work could also help clinicians develop a simpler way to test children for the disorder.

In their study Bryson and Landry observed the reactions of two groups of children, those with autism and those without it, as they watched lights flashing on video screens [*see illustration below*]. The children ranged in age from four to seven. In the first test, each child was placed in front of a three-screen panel, and a flashing light appeared on the middle screen. This stimulus prompted all the children to focus their eyes on the flashes (*a*). Then the middle screen went blank, and a flashing light appeared on the far-right or far-left screen of the panel. Both groups of children shifted their eyes to that screen (*b*). In the second test, however, the lights on the middle screen kept flashing while the lights appeared on the other screen. The children without autism shifted their eyes to focus on the new stimulus (*c*), but the children with autism remained "stuck" on the first stimulus and failed to turn their eyes to the new one (*d*). The two tests were repeated many times for each child.



DANIELS & DANIELS

London had studied different knockout strains with similar results. They found that the gene is active in the brain stem when the first neurons are forming—the same period that Miller and Strömland had identified as the time when thalidomide caused autism. *Hoxa1* produces a type of protein called a transcription factor, which modulates the activity of other genes. What is more, *Hoxa1* is not active in any tissue after early embryogenesis. If a gene is active throughout life, as many are, altered function of that gene usually leads to problems that increase with age. A gene active only during development is a better candidate to explain a congenital disability like autism, which seems to be stable after childhood.

Hoxa1 is what geneticists call a "highly conserved" gene, meaning that the sequence of nucleotides that make up its DNA has changed little over the course of evolution. We assume that this is a characteristic of genes that are critical to survival: they suffer mutations as other genes do, but most changes are likely to be fatal, so they are rarely passed on to subsequent generations. Although many other genes appear in several forms—for example, the genes that encode eye color or blood type—highly conserved genes are not commonly found in multiple versions (also known as polymorphic alleles, or allelic variants). The fact that no one had ever discovered a variant of *Hoxa1* in any mammalian species suggested that my colleagues and I might have trouble finding one in cases of autism. On the other hand, it seemed likely that if a variant allele could be found, it might well be one of the triggers for the development of the disorder.

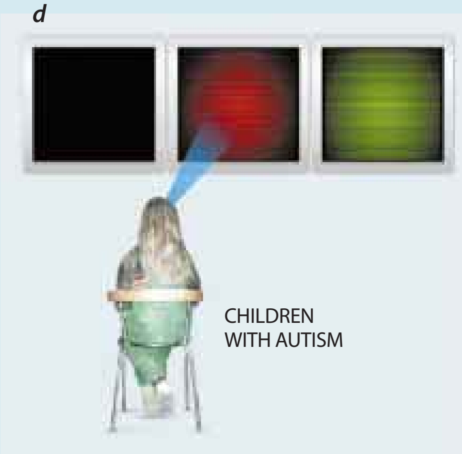
Zeroing in on *HOXA1*

The human version of the gene, labeled as *HOXA1*, resides on chromosome 7 and is relatively small. It contains just two protein-coding regions, or exons, along with regions that regulate the level of protein production or do nothing at all. Deviations from the normal sequence in any part of a gene can affect its performance, but the vast majority of disease-causing variations are in the protein-coding regions. Thus, we began the search for variant alleles by focusing on the exons of *HOXA1*. Using blood samples from people with autism and from subjects in a control group, we extracted the DNA and looked for deviations from the normal sequence of nucleotides.

The good news is that we have identified two variant alleles of *HOXA1*. One has a minor deviation in the sequence of one of the gene's exons, meaning that the protein encoded by the variant gene is slightly different from the protein encoded by the normal gene. We have studied this newly discovered allele in detail, measuring its prevalence among various groups of people to determine if it plays a role in causing autism. (The other variant allele is more difficult to investigate because it involves a change in the physical structure of the gene's DNA.)

Bryson and Landry found that children with other kinds of brain damage are perfectly normal in their ability to disengage from one stimulus and focus on another. Children with autism, however, repeatedly fail to disengage from the first stimulus, even if they are highly intelligent. Researchers suspect that this ability is a low-level brain function because it typically appears in infants—as early as three to four months after birth—and in children with low IQs. Animals also orient themselves toward new stimuli, so scientists could conceivably use a similar test in animal studies to verify whether genetic manipulations or toxicologic exposures have produced this symptom of autism. *—P.M.R.*

d



We found that the rate of the variant allele among people with autism was significantly higher than the rate among their family members who do not have the disorder and the rate among unrelated individuals without the disorder. The differences were much greater than would be expected by chance.

The bad news is that, just as the family studies had predicted, *HOXA1* is only one of many genes involved in the spectrum of autism disorders. Furthermore, the allele that we have studied in detail is variably expressed—its presence does not guarantee that autism will arise. Preliminary data indicate that the variant allele occurs in about 20 percent of the people who do not have autism and in about 40 percent of those who do. The allele approximately doubles the risk of developing the condition. But in about 60 percent of people with autism, the allele is not present, meaning that other genetic factors must be contributing to the disorder.

To pin down those factors, we must continue searching for other variants in *HOXA1,* because most genetic disorders result from many different deviant alleles of the same gene. Variations in other genes involved in early development may also predispose their carriers to autism. We have already discovered a variant allele of *HOXB1,* a gene on chromosome 17 that is derived from the same ancestral source as *HOXA1* and has similar functions in the development of the brain stem, but its effect in autism appears to be minor. Other investigators are scrutinizing candidate regions on chromosome 15 and on another part of chromosome 7. Although researchers are focusing on alleles that increase the risk of autism, other alleles may decrease the risk. These could help explain the variable expression of the spectrum of autism-related disorders.

Even a minimal understanding of the genetic basis of autism would be of great value. For example, researchers could transfer the alleles associated with autism from humans to mice, engineering them to be genetically susceptible to the disorder. By exposing these mice to substances suspected of increasing the risk of autism, we would be able to study the interaction of environmental factors with genetic background and perhaps compile an expanded list of substances that women need to avoid during early pregnancy. What is more, by examining the development of these genetically engineered mice, we could learn more about the brain damage that underlies autism. If researchers can determine exactly what is wrong with the brains of people with autism, they may be able to suggest drug therapies or other treatments that could ameliorate the effects of the damage.

Devising a genetic test for autism—similar to the current tests for cystic fibrosis, sickle cell anemia and other diseases—would be a much more difficult task. Because so many genes appear to be involved in the disorder, one cannot accurately predict the odds of having a child with autism by simply testing for one or two variant alleles in the parents. Tests might be developed, however, for the siblings of people with autism, who often fear that their own children will inherit the disorder. Clinicians could look for a set of well-established genetic risk factors in both the family member with autism and the unaffected sibling. If the person with autism has several high-risk alleles, whereas the sibling does not, the sibling would at least be reassured that his or her offspring would not be subject to the known risks within his or her family.

Nothing will make the search for autism's causes simple. But every risk factor that we are able to identify takes away some of the mystery. More important, new data spawn new hypotheses. Just as the thalidomide results drew attention to the brain stem and to the *HOXA1* gene, new data from developmental genetics, behavioral studies, brain imaging and many other sources can be expected to produce more welcome shocks of recognition for investigators of autism. In time, their work may help alleviate the terrible suffering caused by the disorder. SA

The Author

PATRICIA M. RODIER is professor of obstetrics and gynecology at the University of Rochester. She has studied injuries to the developing nervous system since she was a postdoctoral fellow in embryology at the University of Virginia, but she began to investigate autism only after hearing the results of the thalidomide study. Rodier has assembled a group of scientists from many disciplines at six institutions to study the genetic and environmental causes of the disorder and says that working with experts from other fields is rejuvenating.

Further Information

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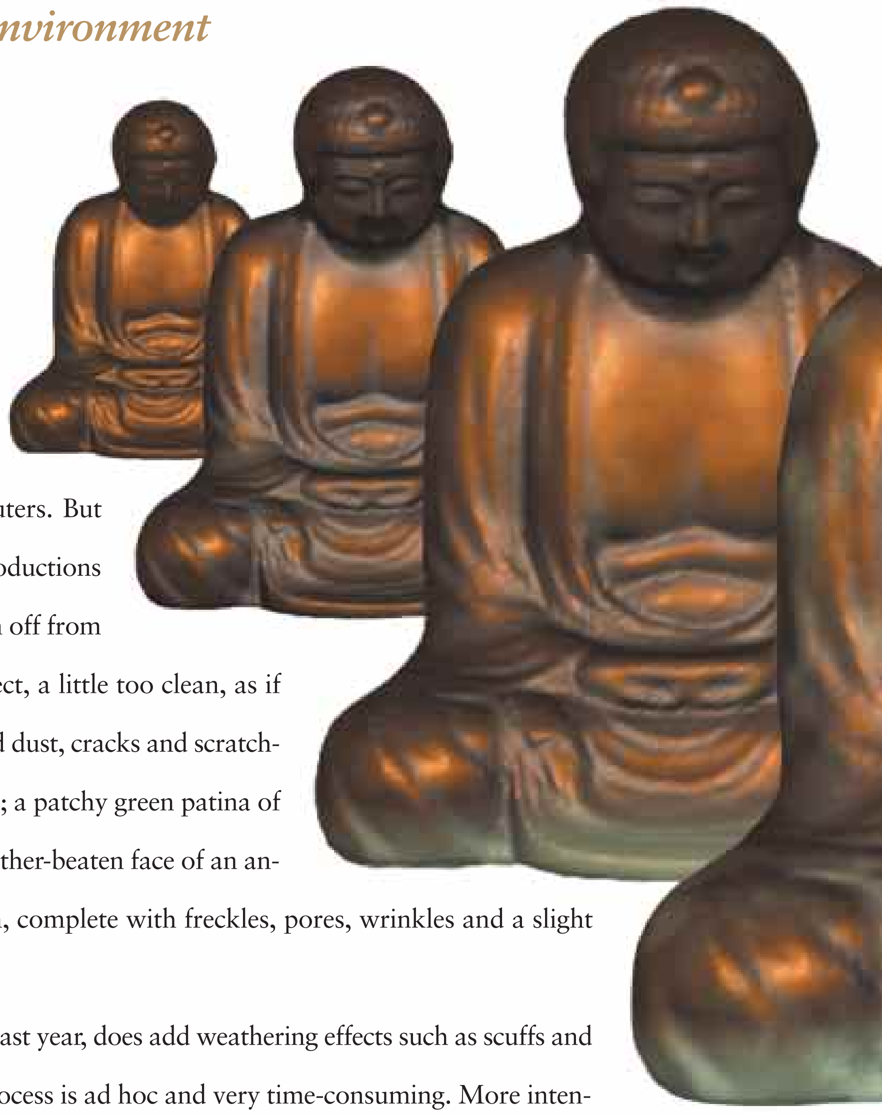
More information on autism is available at the Web page of the National Alliance for Autism Research at www.naar.org

Digital Materials and

The next step in creating more realistic computer-generated images is the development of better models of the physical structures of materials and their degradation by the environment

by Julie Dorsey and Pat Hanrahan



JULIE DORSEY AND PAT HANRAHAN

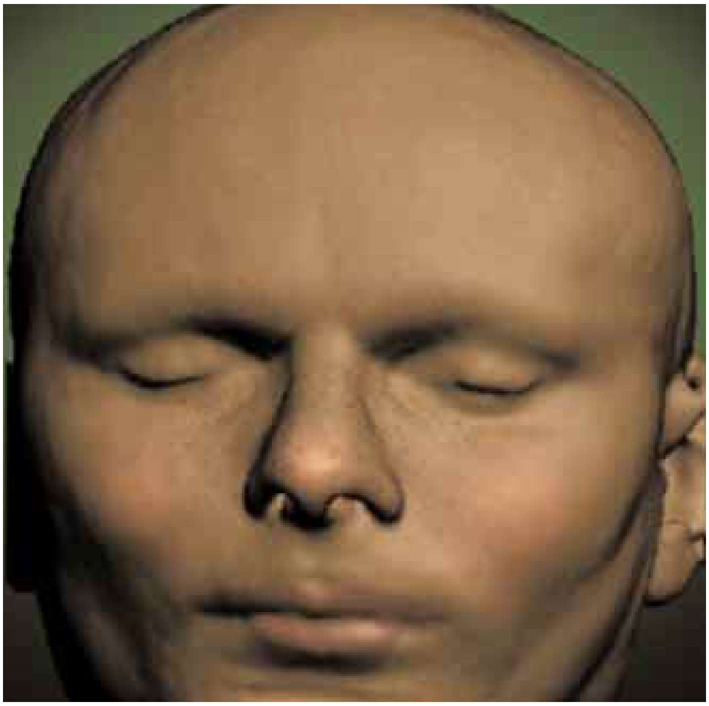
Computer graphics passed an entertainment milestone in 1995 with the release of *Toy Story,* the first full-length movie animated using computers. But the digitally created characters and sets of such productions generally still have a distinctive look that sets them off from reality: everything is a little too smooth and perfect, a little too clean, as if freshly molded in plastic. What's missing is dirt and dust, cracks and scratches; a dribble of rust down a wall from a leaky pipe; a patchy green patina of oxidation on a copper statue; the salt-crusted, weather-beaten face of an ancient granite sphinx; the fine tones of human skin, complete with freckles, pores, wrinkles and a slight flush of living blood.

The Pixar team, which released *Toy Story 2* late last year, does add weathering effects such as scuffs and dirt by painting patterns onto surfaces, but this process is ad hoc and very time-consuming. More intensive application of these established techniques or brute-force application of greater computing power will not be enough to overcome the cartoonish, waxen look of computer graphics. To produce a simulation that doesn't *look* like one, we must properly model the appearance of materials in all their variety, including realistic wear and grime. Techniques such as ray tracing and radiosity, which simulate lighting, can add to the ambience of virtual scenes with effects such as soft shadows and reflections, but the accuracy and visual complexity of the resulting images also depend crucially on the quality of the underlying material models.

Such models are becoming increasingly realistic. An important feature of them is explicit modeling of a material's

Virtual Weathering

PATINA DEVELOPMENT ON A COPPER BUDDHA is simulated using a series of layers to represent the physical structure of the surface. Different operations oxidize the top layer and remove loose material as if under the action of wind and rain. Interaction of light with the stack of layers determines the resulting appearance.



PAT HANRAHAN AND WOLFGANG KRUEGER

HUMAN SKIN is among the most challenging appearances to simulate well. This image models the interaction of light with the outer epidermis and the underlying, blood-rich dermis. The lips, for example, are pink because of their thin epidermis. The data for this image were obtained by a medical MRI scan.

internal structure and the simulation of light propagation and scattering beneath its surface. Another is the modeling of how a surface evolves under aging phenomena such as corrosion, which can add irregular layers of oxides and also break away pieces of the surface. An exciting possibility for the future would be a palette of software tools enabling artists to "brush on" physical processes of this kind, in the same way that they can apply "paint" and other coloring effects on screen today.

Such image-making, or rendering, technology is becoming widely used in industry and not merely in animated movies. Boeing used rendering technology for virtual-reality systems to design its 777 aircraft. Architecture firms and city planners use rendering to assess the visual impact of proposed buildings on neighborhoods.

Ray Tracing, Reflection and Texture

Scientists and artists have long theorized about the causes of appearance in the natural world. During the 17th century, Rembrandt and other Dutch and Flemish artists reproduced natural skin tones in their lifelike portraits by applying multiple layers of paint and lacquer. In the 19th century Lord Rayleigh used principles of physics to explain the sky's blue color, the iridescence in butterfly wings and the shine of polished surfaces. Today we can use such theories and insights to create practical computer simulations of the mechanisms that generate different appearances.

The rendering of realistic computer images requires simulating light and its interaction with the environment, which includes objects (such as sets, props and characters), lights that shine on them and a virtual camera that observes the scene. The objects are defined by their shapes, positions, orientations and materials. Once the scene has been modeled, the rendering program computes the paths that light follows from the light sources to the camera [*see upper illustration on page 70*].

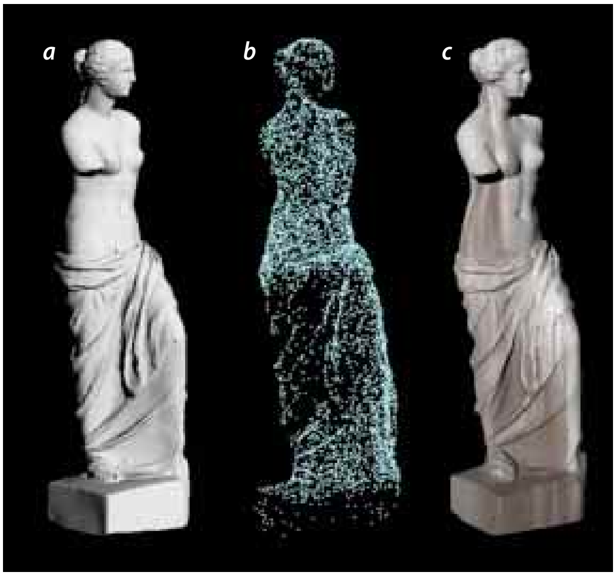
Several techniques may be used to simulate light propagation. The radiosity method models how light reflected from a matte surface illuminates the surrounding area. Ray tracing tracks rays of light one bounce at a time. The current state-of-the-art technique is stochastic ray tracing: rays hitting a surface are reflected randomly in different directions according to probabilities that may depend on properties of the surface or other parts of the environment. This technique can reliably simulate the interaction of light with a wide variety of complex shapes and materials.

The basic methods for rendering were developed during a few groundbreaking years in the 1970s at the University of Utah. These early shading models were hybrids, combining aspects of lighting simulation, reflection models and interpolation. Shapes were often approximated by a mesh of triangles. Henri Gouraud developed a method whereby the vertex of each triangle was lit and the color of the reflected light was interpolated across the triangle. Lance Williams and Edwin Catmull (later a co-founder of Pixar) first proposed texture mapping, in which the color of an object is controlled by an image that is mapped onto the three-dimensional shape of the object's surface, similar to the pasting of a decal on a plastic toy.

The earliest computer graphics models of how light reflects from objects tried to capture the major aspects of appearance by simple formulas, without drawing on physical principles to simulate the interaction of light with matter. These phenomenological reflection models, as they are called, use a mathematical function called the bidirectional reflectance distribution function, or BRDF [*see box on page 69*]. Types of BRDFs range from those of matte materials such as cardboard, which scatter light equally in all directions (Lambert's Law of Reflection), to those of perfect mirrors, which reflect a ray of light in a single direction [*see lower illustration on page 70*]. Between these extremes, shiny surfaces produce a distribution of reflected light roughly centered in one direction. Such surfaces are typically modeled by adjusting the size of the shiniest spots of reflected light.

In computer graphics, texture and reflection are considered separate aspects of appearance. In fact, visual texture is more distinctive than the reflective property for most materials, so generating and using textures to control the reflective properties at different points on the surface is an important ability. Two techniques are widely used to create combinations of texture and reflection: procedural models based on shading and direct three-dimensional painting. These two approaches represent different ends of the spectrum, one highly programmed and the other highly interactive.

A procedural model requires a computer program to generate the desired pattern. For example, a wood pattern can be defined by an algorithm that creates a solid texture of 3-D concentric rings. The ring pattern then controls the color and intensity of light reflected from pieces such as table legs carved from the wood. At the other extreme, in direct 3-D painting the artist applies simulated paint to a 3-D shape. The paint's properties determine the material's appearance, and patterning is obtained by applying different strokes on different parts of the shape. Because the 3-D painting metaphor is natural and intuitive to an artist and because such systems give the user immediate feedback by instantly displaying chang-



ALL IMAGES BY JULIE DORSEY, HANS PEDERSEN AND PAT HANRAHAN

EFFECTS OF RAINWATER and dirt on a replica of the Venus de Milo (*above, a*) were simulated using a model of individual raindrops (*b*) to yield a dirt-streaked statue (*c*). A similar process simulated the effects of rainwater flows on a building facade (*right*).

es, they are widely used in the entertainment industry.

Although these approaches are very powerful, they have several limitations. First, they are often tedious and labor-intensive: imagine painting a complex stone pattern on a building. Clearly, algorithmic techniques could help with this process. Second, as the use of computer-generated images becomes more widespread, a greater range of appearances must be simulated. Ad hoc techniques that work well enough for specific objects and applications soon run up against their limits. The desire to go beyond these limits has spurred a new trend in image-synthesis techniques: the inclusion of more information about material structure and the interaction of light with matter.

Roughing It Up

The roughness of a surface is a good example of a material structure that affects appearance. Metal that has been brushed or machined often contains microgrooves etched into its surface. Materials such as cloth contain cross-hatched fibers (the warp and woof) that create bumps and valleys. The features of a surface can also change over time; for instance, when a surface is polished, bumps are removed, making it shinier.

The microgeometry of a rough surface may be modeled by a height field that perturbs the position of the surface by a small amount at each location. These displacements may be given by a random function with specified statistical properties or by a detailed map of the microscopic structures on the surface.

Reflection from rough surfaces was first studied by scientist Pierre Bouguer during the Enlightenment. He assumed that a surface was made up of many "microfacets" (he called them "micro faces"). The amount of light reflected toward a viewer was determined by the proportion of microfacets that were aligned to reflect light directly from the source to the viewer. Bouguer hoped to explain Lambert's Law, which describes the appearance of matte surfaces, by constructing an arrangement of microfacets that would reflect light equally in all directions, but this was eventually proved to be impossible.

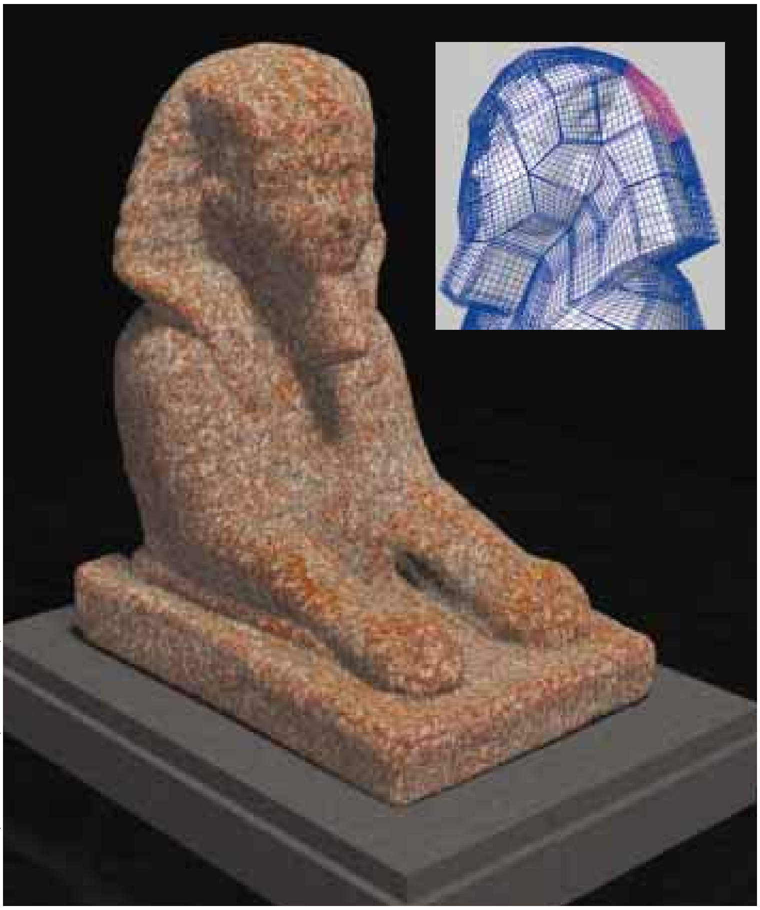
For specular or glossy surfaces, however, microfacets have become the most widely used model. Computer graphics simulations of reflection can directly specify the distribution of microfacet alignments. Typically a simple distribution is used, with a roughness parameter defining how much the microfacets deviate from the main surface shape.

Microfacet distributions have their limits even for glossy surfaces. For example, when light strikes a rough surface from a low angle, the high peaks will shadow the valleys, dramatically changing the appearance of the surface. Unfortunately, computing such "self-shadowing" effects for microfacet distributions is very difficult. An even more complex problem arises when the wavelength of light is comparable to the size of the surface undulations; then Bouguer's simple model of reflection does not apply, and wave effects such as diffraction and interference can come into play.

More Than Skin Deep

Surprisingly, the physical process of reflection from many materials does not result from light interacting with the surface itself, that is, with the infinitesimal interface between the air and the medium. Instead interactions occur inside the material. This phenomenon, subsurface scattering, is common in organic materials, as well as plastics and other composite materials. The relevant depth can range from microns in the case of paint or other coatings to millimeters in the case of skin or marble.

In subsurface reflection, light crosses the interface into a material. Inside, the light is scattered and absorbed by the con-



JULIE DORSEY, ALAN EDELMAN, HENRIK JENSEN, JUSTIN LEGAKIS AND HANS PEDERSEN

WEATHERING OF A GRANITE SPHINX is simulated using a three-dimensional shell (*inset*) that extends from the stone surface into the interior. Water and contaminants invade this shell, inducing chemical changes and producing decayed minerals, recrystallized salts and an eroded crust.

stituents of the medium, such as individual atoms or molecules, similar to how light might interact with a misty cloud of water vapor. Scattered light can travel back to the surface and exit the medium, appearing to the observer as reflected light. Most of the scattering events in the medium are like glancing blows that deflect the light by less than 90 degrees, and so it can take many such collisions to redirect light back toward the outside. As more deflections occur, the directions of light propagation become randomized. This process, which predicts that light may exit the material in a random direction, is thought to be the mechanism that gives rise to Lambert's Law.

The theory of scattering in a layered media was originally developed to explain radiative transport—the movement of heat and light by radiation—in planetary and solar atmospheres. It has been further developed by researchers interested in the appearance of paint, skin, vegetation and the ocean. Such models have recently been adapted to computer graphics. Interestingly, a clean painted wall and the fine skin tones of a person's face, which are respectively among the simplest and most challenging of appearances to model, are both well described by subsurface scattering.

As anyone who has gone to the hardware store to buy a can of paint knows, the paint mixer starts with white paint. The paint's whiteness comes from titanium dioxide, which is an almost perfect scatterer and does not absorb any light. When light falls on a surface painted matte white, the light enters the coat of paint and is scattered many times by the suspended titanium dioxide particles, ultimately exiting the paint and returning to the environment. The whiteness of the surface occurs because very little light is absorbed, and all the visible wavelengths of light are returned equally. The multiple scattering inside the paint and the resulting randomization of the light's direction account for the matte appearance.

To create a colored paint, a small amount of pigment is added to the white paint and mixed. These pigments are chemicals that selectively absorb certain wavelengths. Because the pigment particles are suspended in a nearly perfect scattering media, eventually the light interacts with a pigment particle and is partially absorbed; the exiting light takes on the color of those wavelengths that are not absorbed. A model for this process was originally introduced by P. Kubelka and F. Munk in 1931. They assumed that the medium contains particles that scatter and absorb light equally in all directions, and they deduced the color and intensity of the light returning from the medium as a function of its thickness and the concentrations of pigment particles. Their model can be used to simulate the color changes caused by varying the thickness of the coat of paint or by mixing different pigments together. They also showed how to calculate the effects of multiple layers of paint, each with a different color or composition.

The Kubelka-Munk model is the simplest and most widely used model for subsurface reflection. But because it assumes that the particles scatter light equally in all directions, it works only for matte materials. Subsurface reflection can also distribute light in preferred directions, as occurs with glossy surfaces, and models have been devised to account for these effects. The basic idea of these models is to allow directional scattering by the particles. The returning light is approximated by dividing it into two parts: the first is light that exits the material after a single sharp scattering event, and the second is the remaining light that is scattered many times. As in the Kubelka-Munk model, the multiply scattered light is assumed to obey Lambert's Law, but the light from single scattering events is distributed according to the scattering function of the relevant particle.

We have applied these ideas to model the appearance of skin, which has long been a key material that computer graphics systems have striven to simulate, without much success. Skin is particularly challenging both because it has a complicated structure and because our human visual systems are highly tuned toward perceiving faces. Subsurface scattering from multiple layers turns out to be quite effective at meeting these challenges.

Human skin consists of two major layers: the inner dermis and the outer epidermis. The dermis is rich in blood, making it red. The epidermis is thinner than the dermis but contains melanin—increasing concentrations of melanin makes the epidermis brown or black. Also, the epidermis may be covered by oil, dirt or cosmetics.

To generate realistic images of faces, we can control the simulated concentrations of blood and melanin and also the relative thicknesses of the dermis and epidermis. For example, because the lips contain only a very thin layer of epidermis, they look redder than the rest of the face. Freckles are modeled by splotches of additional melanin scattered randomly on the cheeks [*see illustration on page 66*].

Early computer graphics models were idealized: by default,

Modeling Reflection

The reflection of light from a surface may be characterized by the BRDF, or bidirectional reflectance distribution function. This mathematical function specifies the percentage of light arriving from each incoming direction that is reflected in each outgoing direction.

The oldest reflection model is the Law of Reflection, known to the ancient Greeks, that says the angle of reflection is equal to the angle of incidence. For a given incoming direction, this is described by a BRDF that is zero in all directions except in the single outgoing direction where all the light goes.

Another reflection model is Lambert's Law, which states that light reflects equally in all directions, independent of the incoming direction. Lambert's Law is a good example of a phenomenological model, because it nicely captures the appearance of matte materials such as cardboard, without describing a physical mechanism that would cause light to be equally reflected in any direction. In fact, explaining Lambert's Law from underlying principles has been a challenge to researchers throughout history. Between the extremes of mirrors and matte surfaces, shiny surfaces have BRDFs that describe a distribution of reflected light roughly centered in one direction.

The BRDFs of materials have been measured directly for many years by optical and radar engineers and others interested in the properties of exotic materials. Such measurements were no doubt important in designing stealth aircraft. BRDFs also interest scientists doing remote sensing of the earth's surface from satellites: the appearance of forest, crops and so on varies according to the angle of the sun and the satellite's viewing angle. This problem is the inverse of simulating the look of a material: deducing a material based on its appearance.

An instrument designed to measure BRDFs is shown at the left. In the instrument, constructed at Stanford University, a small sample is placed in the center, a light source shines on the sample, and a photometer systematically moves to different positions on the hemisphere, measuring the light reflected in each of those directions. The measurements are repeated with the light source moved to all positions on the hemisphere to acquire the material's entire BRDF. Measured BRDFs have yet to find wide use in computer graphics, but several groups are pursuing this approach. *—J.D. and P.H.*

Measuring an object's reflectance.

MARC LEVOY, BRIAN CURLESS, SZYMON RUSINKIEWICZ AND DUANE FULK *Stanford University*

they assumed the materials to be in pristine condition. In reality, of course, all materials change when exposed to the surrounding environment. Some of the richest appearances in the real world—mellowed brickwork, rusty metal, moss-covered stone, seasoned timber—arise from physical processes such as corrosion, erosion, biological growth and sedimentation. A material's tendency to weather is closely linked to its structure. Stone, wood and metals weather quite differently because of their distinct structures. Methods of preparation such as quarrying, polishing and staining are also important. We have recently begun to develop models for some of these processes that affect appearance, first identifying the basic physical phenomena that underlie a specific change in appearance and then developing the appropriate computer models.

Simulating Corrosion

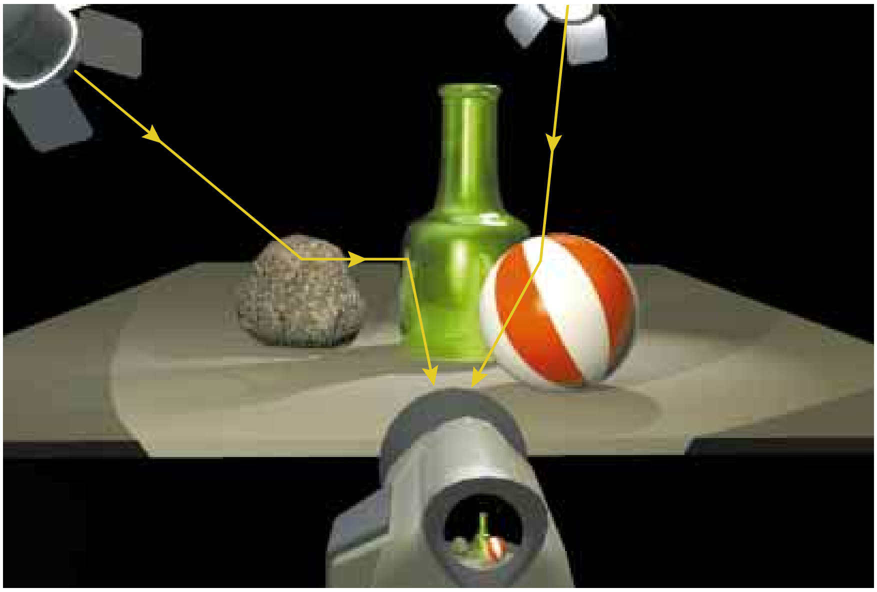
Metallic patinas are a classic case of appearances that develop when materials interact with their environment. A patina is a film or encrustation on a surface that is produced by chemical alteration or by the addition or removal of material. Patinas can develop naturally through atmospheric corrosion or artificially through painting or other craft processes. A patina's composition and rate of development depend on the surrounding environment. For example, patinas generally develop more rapidly in urban settings than in rural areas because city air has higher concentrations of sulfur. Rainwater and other factors also play an important role in the formation of patinas.

We have developed a phenomenological model for the development of copper patinas. The surface is represented as a series of layers, and patinas are formed by applying a collection of intuitive operators, such as "coat," "erode" and "polish," to the layered structure. For instance, applying "coat" to a region adds some oxide to the top layer. "Erode" simulates the removal of loose material through the action of wind or rain. To simulate detailed variations in thickness over time, we have experimented with a series of models for use with the layer structure in which a patina grows across the surface in a fractal pattern. (Fractals have been put to great use in computer graphics, such as the generation of realistic-looking terrain, vegetation and so on.) The final appearance of the copper patina depends on how light interacts with the stack of layers, for which we use the Kubelka-Munk model [*see illustration on pages 64 and 65*].

The flow of rainwater is one of the most important and pervasive natural forces contributing to the weathering of materials, producing distinctive patterns. Water may clean some areas by washing dirt away, while staining other areas by depositing dirt and other substances. To simulate these processes we have developed a simple "particle" model of water flow.

Each particle represents a drop of water. The motion of each particle is controlled by factors such as gravity, friction, wind, roughness and constraints that keep the particles in contact with the surface. A set of equations govern the chemical interaction of the water and the surface materials: they describe the rate at which the surface absorbs water and the rate of solubility and sedimentation of deposits on the surface. The illustration on page 67 shows the result of applying the model to simulate washing and staining patterns produced on a facsimile of the classic Venus de Milo statue.

We began with a uniform coating of dirt on the statue and then ran a flow simulation to wash the surface. The flow produced noticeable streaks in the dirt patterns, along with a randomness because of the individual particles. Dirt accumulated where the surface was protected from the path of the



INTERACTION OF LIGHT and its environment must be simulated to render realistic computer images. The environment includes light sources, objects, and cameras watching the scene. The simulation must deal with glossy and matte surfaces and visual textures.

flow, such as under the arm. The dirt pattern conformed to the folds in the fabric; for example, the upper surfaces of the convex parts of the folds were clean, whereas the lower surfaces were dirty. The pattern is more uniform on the base of the statue and closer to the ground, because less water reached those areas. The illustration on page 67 also shows the results of such water flows applied to a building facade.

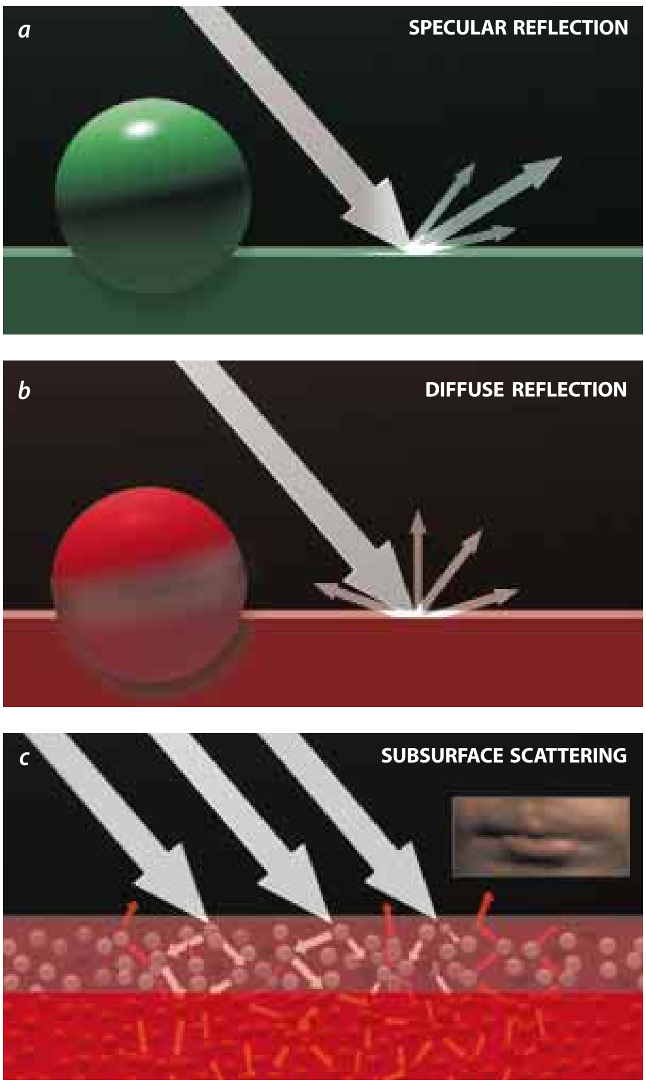
Both the copper patinas and the "particle" model of water flow simulate only surface effects; that is, the changes in appearance involve just a thin skin near the actual surface. More recently, we have begun investigating models and processes that are more volumetric in nature, such as the erosion of stone. Stone consists of one or more minerals joined together in a tight fabric. The arrangement of this fabric characterizes the type of stone and partly determines its physical and chemical properties, including its strength, color and durability.

Rocks of Ages

Like metals, stone exposed to the environment is attacked by atmospheric contaminants such as the oxides of carbon, sulfur and nitrogen that in water form the infamous acid rain. Instead of being confined to the surface, this solution penetrates some distance into the stone. The penetrated rock can be changed chemically, and recrystallization can produce a crust that is typically more fragile than the native fabric of the stone. Eventually pieces of the crust break off, exposing fresh stone to further attack. Thus, the net effects of stone weathering include color changes, formation of dirty crusts, erosion of surfaces and structural damage such as cracking.

The illustration on page 68 shows a simulation of a small red granite sphinx that has been exposed to such processes. We model the statue as a shell of stone at the statue's surface that extends a significant thickness into the interior. A three-dimensional function describes which minerals are present throughout the stone fabric of this "volumetric surface." The environmental model includes sources of water and contaminants, and these induce reactions on the surface and inside the shell. In this way, the model generates a complicated surface microgeometry and an intricate volumetric mixture of minerals. To render the translucency and coloration caused by the minerals near the surface, we simulate the scattering of light inside the stone using stochastic ray tracing.

A difficult problem, one that occurs generally in computer graphics, is to avoid having to do an excessive number of computations without compromising the quality of the image. For example, for scenes in which an eroded statue appears in the background, it may be appropriate to replace bump maps (which simulate small geometric irregularities of the surface) with a distribution of microfacets that produce the right texture with a much lower computational overhead. As the camera's viewpoint shifts and the statue moves into the fore-



ALFRED T. KAMAJIAN

REFLECTIONS FROM SURFACES are a crucial element of image-rendering systems. Specular reflections (*a*) produce shiny surfaces with highlights. Simple matte materials such as cardboard can be modeled using diffuse reflections (*b*) that scatter light equally in all directions. In many materials, subsurface interactions (*c*) play an important role in generating the appearance.

ground, however, a detailed map of the surface becomes essential for producing a realistic effect [*see box at right*].

Challenges

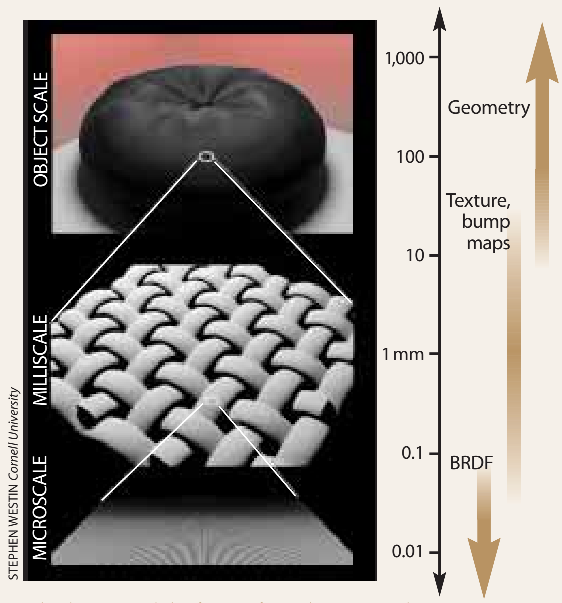
The development of material models for computer graphics is only just beginning, but it has already raised some key issues about the models' limitations and trade-offs. Many aspects of appearance are not well understood from physical principles. The corrosion of metals, for example, has tremendous scientific interest and obvious practical importance, but scientists' understanding of the process is far from complete. In addition, the variety of applications that make use of rendering technology places different demands on the accuracy of the models. For instance, in movie production work, appearances merely need to look right—physical accuracy is of secondary importance. In some engineering and scientific applications, however, physical accuracy is critical—creating a different set of expectations for the underlying models. We can see this trade-off in the skin model: although it is convincing enough for many applications, it does not include such elements as hair follicles, pores and oil glands, which would probably be of interest to dermatologists or biologists.

The problem of creating physically based models of materials that can incorporate variations over time is an important challenge for computer graphics. What is needed is a more comprehensive set of models of materials and the processes that affect their appearance. Ideally, computer scientists could create broad taxonomies of materials for easy access by an array of users—much the way people use clip art today. As researchers gain insight into the structure of materials and develop new computer models, a host of new design and engineering applications could reap the benefits. Automobile designers might study various coatings applied to virtual cars to understand the structure, appearance and performance of coatings over time. Architects and conservators might be able to simulate the long-term durability of materials and study the different ways to preserve them. Finally, computer models of materials could even help designers create entirely new appearances—an accomplishment that would beautify the world, not just imitate it. SA

Levels of Detail

Computer graphics systems must cope with scenes containing millions of basic geometric shapes, and they often must perform millions of BRDF calculations to make a single image. The use of material models in real applications therefore requires skill to minimize the number of computations. This can be as simple as computing or approximating reflection functions during a preparatory process and saving the results for quick lookup during the actual rendering.

Another key technique is to introduce a hierarchy of abstractions and to use the right one at the right time. If the camera has zoomed in for a close-up of an object, fine detail of the surface should be visible and must be modeled explicitly. But as the camera pulls back and the scale changes, the finest details will no longer be distinctive and may be replaced by simpler approximations. For example, a rough surface may be modeled using a height field, and for close-ups these irregularities may be displayed as visible geometric displacements—the finely detailed bumps and crevices of the surface. For medium shots, only the average smooth shape of the surface may be resolvable, and the roughness can be represented merely through subtle variations in the shading and perhaps some patches of self-shadowing. On long shots, a microfacet distribution might be sufficient.



The best model of a surface, here a cushion, depends on the required level of detail.

Automatically changing the representation and computation of material properties as we zoom in and out is a challenging problem of great current interest. How can we produce a computer program that switches automatically to the appropriate level of detail? The scenes in today's applications are extremely complex, often containing tens of millions of surfaces, so for computational efficiency it is crucial to use the simplest possible approximation for each element. —*J.D. and P.H.*

The Authors

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Further Information

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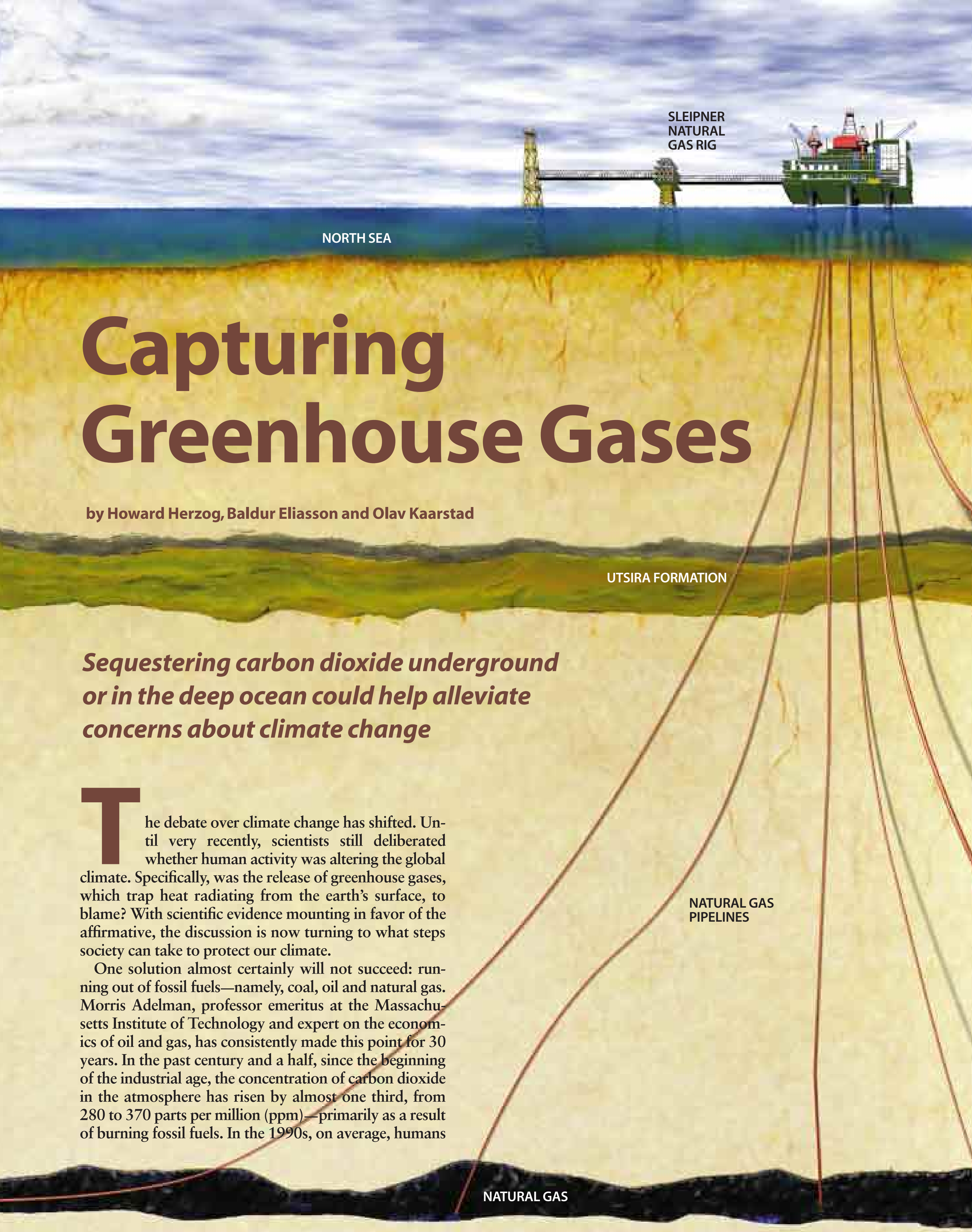
Further information and images are available on the Web at http://graphics.lcs.mit.edu/materials/



Capturing Greenhouse Gases

by Howard Herzog, Baldur Eliasson and Olav Kaarstad

Sequestering carbon dioxide underground or in the deep ocean could help alleviate concerns about climate change

The debate over climate change has shifted. Until very recently, scientists still deliberated whether human activity was altering the global climate. Specifically, was the release of greenhouse gases, which trap heat radiating from the earth's surface, to blame? With scientific evidence mounting in favor of the affirmative, the discussion is now turning to what steps society can take to protect our climate.

One solution almost certainly will not succeed: running out of fossil fuels—namely, coal, oil and natural gas. Morris Adelman, professor emeritus at the Massachusetts Institute of Technology and expert on the economics of oil and gas, has consistently made this point for 30 years. In the past century and a half, since the beginning of the industrial age, the concentration of carbon dioxide in the atmosphere has risen by almost one third, from 280 to 370 parts per million (ppm)—primarily as a result of burning fossil fuels. In the 1990s, on average, humans

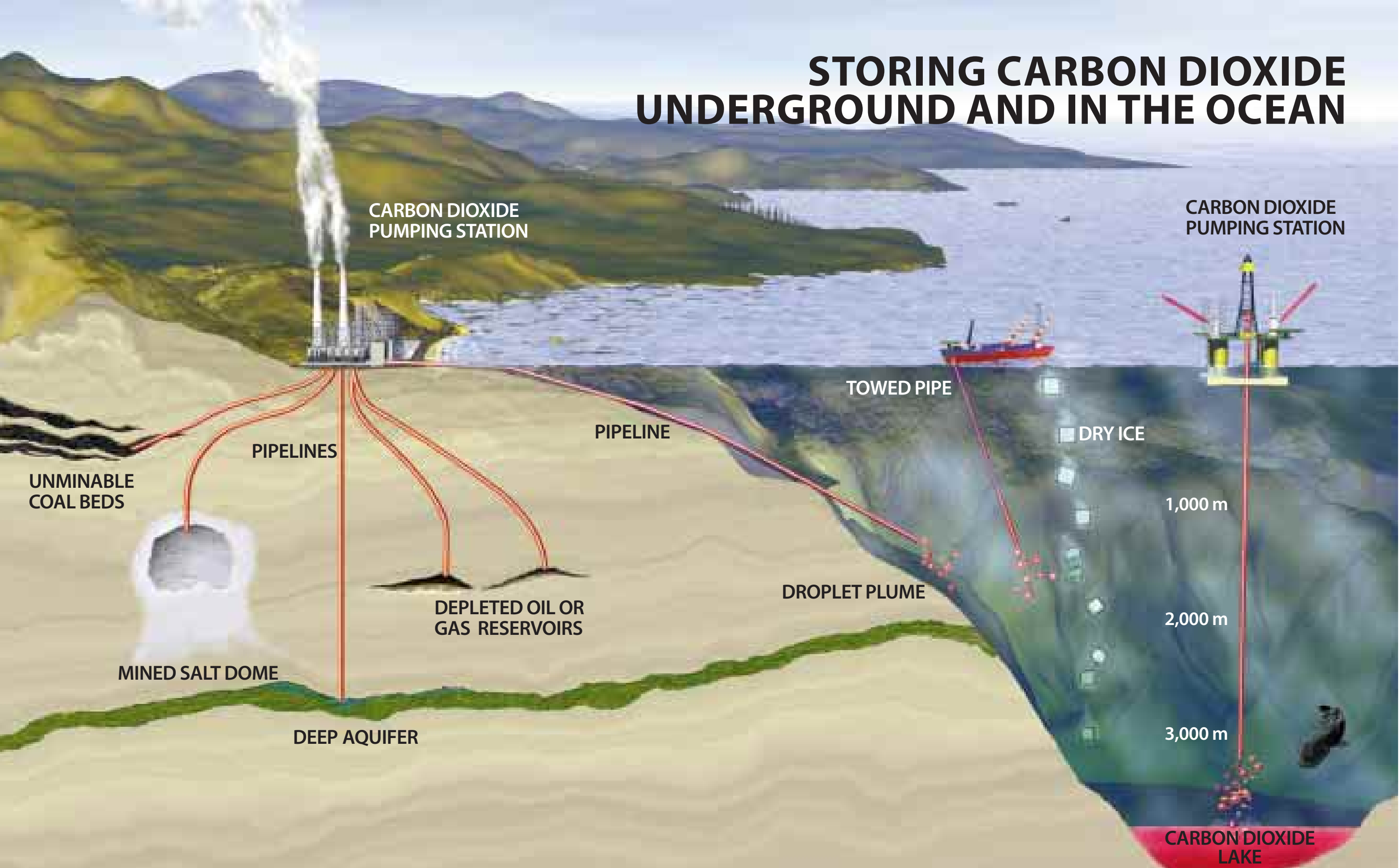
DEEP UNDERGROUND, some 1,000 meters below the bottom of the North Sea, carbon dioxide is pumped into the sandstone reservoir known as the Utsira Formation, where it can be stored for thousands of years. To avoid Norway's carbon dioxide tax, the owners of the Sleipner natural gas rig, located some 240 kilometers from the Norwegian coast, now bury the greenhouse gas that would otherwise be released from the rig into the atmosphere.

DAVID FIERSTEIN

discharged 1.5 ppm of carbon dioxide annually; with each passing year, the rate increased. Even though humans release other greenhouse gases, such as methane and nitrous oxide, experts project that carbon dioxide emissions will account for about two thirds of potential global warming. As apprehension has grown regarding the possible hazards of a changing global climate, environmental groups, governments and certain industries have been trying to reduce the level of greenhouse gases in the atmosphere, often by promoting energy efficiency and alternative energy sources—for instance, wind or solar power.

Realistically, however, fossil fuels are cheap and plentiful and will be powering our cars, homes and factories well into the 21st century and possibly beyond. Worries about diminishing fuel supplies have surfaced periodically over the past 100 years, but continuing improvements in both oil exploration and production technology should keep the fuel flowing for decades to come. Furthermore, since the adoption of the first international treaty designed to stabilize greenhouse gas emissions, signed at the 1992 Earth Summit in Rio de Janeiro, the global demand for fossil fuels has actually increased. Today more than 85 percent of the world's commercial energy needs are supplied by fossil fuels. Although policies that promote energy efficiency and alternative energy sources are crucial to mitigating climate change, they are only one part of the solution.

Indeed, even if society were to cut back the use of fossil fuels today, the planet would still most likely experience significant repercussions as a result of past emissions. The climate's response time is slow, and carbon dioxide remains in the atmosphere for a century or more if left to nature's devices. Therefore, we must have a portfolio of technology options to adequately reduce the accelerating buildup of greenhouse gases. Significant research and development efforts are already exploring ways to improve energy efficiency and increase the use of fuels with no car-



STORAGE UNDERGROUND	ADVANTAGES	DISADVANTAGES	STORAGE IN OCEAN	ADVANTAGES	DISADVANTAGES
Coal Beds	Potentially low costs	Immature technology	Droplet Plume	Minimal environmental effects	Some leakage
Mined Salt Domes	Custom designs	High costs	Towed Pipe	Minimal environmental effects	Some leakage
Deep Saline Aquifers	Large capacity	Unknown storage integrity	Dry Ice	Simple technology	High costs
Depleted Oil or Gas Reservoirs	Proven storage integrity	Limited capacity	Carbon Dioxide Lake	Carbon will remain in ocean for thousands of years	Immature technology

STORAGE SITES for carbon dioxide in the ground and deep sea should help keep the greenhouse gas out of the atmosphere where it now contributes to climate change. The various options must be scrutinized for cost, safety and potential environmental effects.

DAVID FIERSTEIN

bon content (renewable energy sources or nuclear power). But a third approach is attracting notice as people recognize that the first two options will simply not be sufficient: carbon sequestration, the idea of finding reservoirs where carbon dioxide can be stored rather than allowing it to build up in the atmosphere.

Our strategy may surprise some readers. Sequestering carbon is often connected to planting trees: trees (and vegetation in general) absorb carbon dioxide from the air as they grow and hold on to that carbon for their lifetime [*see box on page 77*]. Scientists estimate that, all together, plants currently retain about 600 gigatons of carbon, with another 1,600 gigatons in the soil.

Plants and soils could perhaps sequester another 100 gigatons or more of carbon, but additional sinks will be needed to meet the challenge of escalating greenhouse gas emissions. So during the past 10 years, the three of us have explored another possibility: capturing carbon dioxide from stationary sources—for example, a chemical factory or an electric power plant—and injecting it into the ocean or underground. We are not alone in our efforts but are part of a worldwide research community that includes the International Energy Agency (IEA) Greenhouse Gas Research and Development Program, as well as government and industry programs.

A New Approach in Norway

Sleipner offshore oil and natural gas field is in the middle of the North Sea, some 240 kilometers off the coast of Norway. Workers on one of the natural gas rigs there inject 20,000 tons of carbon dioxide each week into the pores of a sandstone layer 1,000 meters below the seabed. When the injection at Sleipner began in October 1996, it marked the first instance of carbon dioxide being stored in a geologic formation because of climate considerations.

How did this venture come about? One reservoir at Sleipner contains natural gas diluted with 9 percent carbon dioxide—too much for it to be attractive to customers, who generally accept no more than 2.5 percent. So, as is common practice at other natural gas fields around the world, an on-site chemical plant extracted the excess carbon dioxide. At any other installation, this carbon dioxide would simply be released to the atmosphere. But the owners of the Sleipner field—Statoil (where one of us, Kaarstad, works as a researcher), Exxon, Norsk Hydro and Elf—decided to sequester the greenhouse gas by first compressing it and then pumping it down a well into a 200-meter-thick sandstone layer, known as the Utsira Formation, which was originally filled with saltwater. The nearly one million tons of carbon dioxide sequestered at Sleipner last year may not seem large, but in the small country of Norway, it amounts to about 3 percent of total emissions to the atmosphere of this greenhouse gas.

The principal motivation for returning carbon to the ground at Sleipner was the Norwegian offshore carbon dioxide tax, which in 1996 amounted to $50 for every ton of the gas emitted (as of January 1, 2000, the tax was lowered to $38 per ton). The investment in the compression equipment and carbon dioxide well totaled around $80 million. In comparison, if the carbon dioxide had been emitted to the atmosphere, the companies would have owed about $50 million each year between 1996 and 1999. Thus, the savings paid off the investment in only a year and a half.

In other parts of the world, companies are planning similar projects. In the South China Sea, the Natuna field contains natural gas with nearly 71 percent carbon dioxide. Once this field has been developed commercially, the excess carbon dioxide will be sequestered. Other studies are investigating the possibility of storing captured carbon dioxide underground, including within liquefied natural gas installations at the Gorgon field on Australia's Northwest Shelf and the Snøhvit ("Snow White") gas field in the Barents Sea off northern Norway, as well as the oil fields of Alaska's North Slope.

In all the projects now under way or in development, carbon dioxide must be captured for commercial reasons—for instance, to purify natural gas before it can be sold. The choice facing the companies involved is therefore between releasing the greenhouse gas to the atmosphere or storing it. They are not deciding whether to collect the carbon dioxide in the first place. We expect that more such companies needing to reduce carbon dioxide emissions will opt for sequestration in the future, but convincing other businesses to capture carbon dioxide emissions from large point sources such as electric power plants is more difficult because of the costs associated with carbon dioxide collection.

Underground or Underwater

The technology for pumping carbon dioxide into the ground is actually well established—it is essentially the reverse of pumping oil and natural gas out of the ground. In fact, the practice is common at many oil fields today. Injecting carbon dioxide into an existing oil reservoir increases the mobility of the oil inside and thereby enhances the well's productivity. During 1998, U.S. oil field workers pumped a total of about 43 million tons of carbon dioxide into the ground at more than 65 enhanced oil recovery (EOR) projects. Yet this quantity adds up to comparatively little carbon sequestration. In contrast, geologic formations, including saline aquifer formations (such as that at Sleipner), unminable coal beds, depleted oil or gas reservoirs, rock caverns and mined salt domes all around the world, can collectively hold hundreds if not thousands of gigatons of carbon.

Although geologic formations show great promise as storage sites, the largest potential reservoir for anthropogenic carbon dioxide is the deep ocean. Dissolved in its waters, the ocean holds an estimated 40,000 gigatons of carbon (compared with 750 gigatons in the atmosphere), but its capacity is much larger. Even if humans were to add to the ocean an amount of carbon dioxide equivalent to doubling the preindustrial atmospheric concentration of the gas, it would change the carbon content of the deep ocean by less than 2 percent. Indeed, slow-acting, natural processes will direct about 85 percent of present-day emissions into the oceans over hundreds of years. Our idea is to accelerate these events.

For ocean sequestration to be effective, the carbon dioxide must be injected into the sea below the thermocline—the layer of ocean between approximately 100 and 1,000 meters, in which water temperatures decrease dramatically with

THE BASICS

BURYING CARBON DIOXIDE

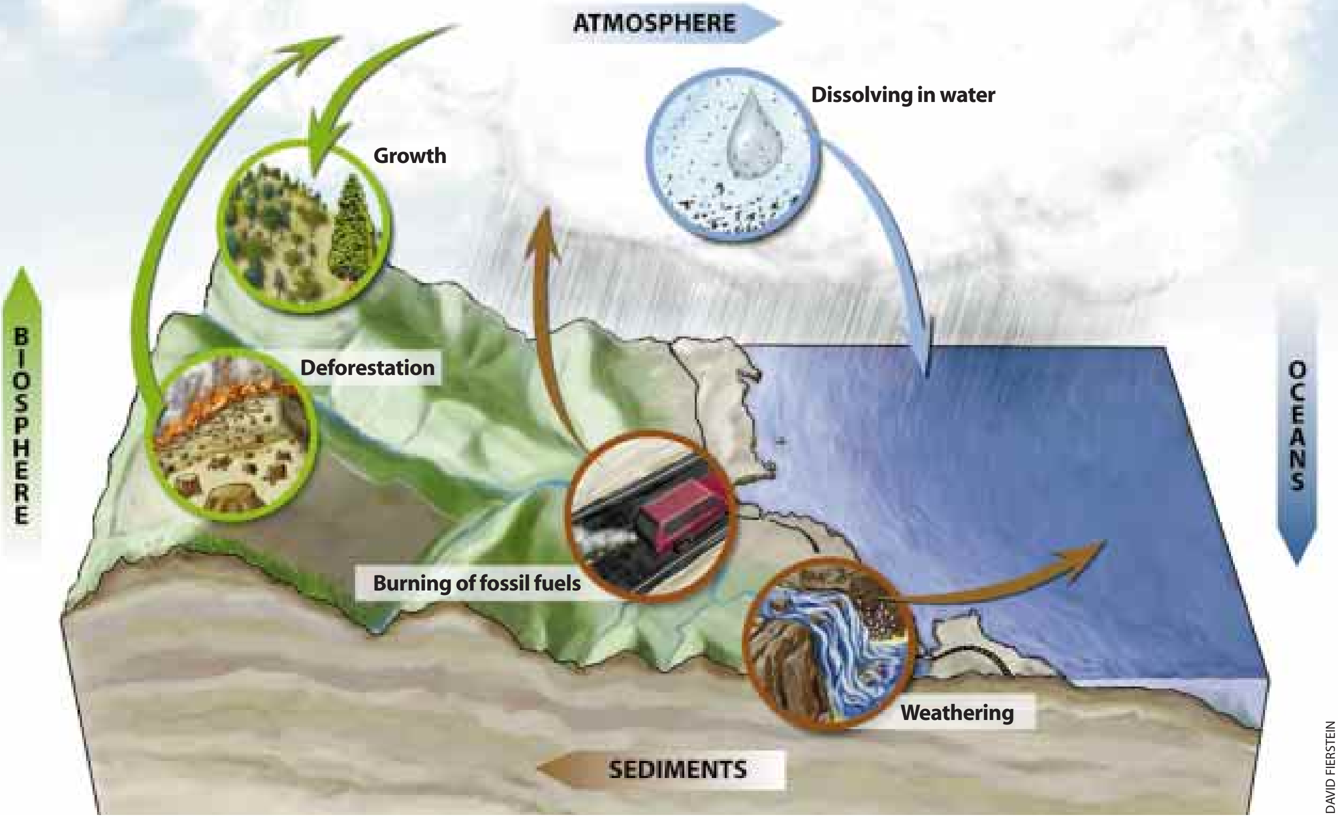
THE AUTHORS REVIEW CARBON SEQUESTRATION TECHNOLOGY

What is carbon sequestration? The idea is to store the greenhouse gas carbon dioxide in natural reservoirs rather than allowing it to build up in the atmosphere. Although sequestering carbon is often connected to planting trees, we are investigating the possibility of capturing carbon dioxide from stationary sources—an electric power plant, for example—and injecting it into the ocean or underground.

Where exactly will the carbon dioxide be stored? It can be pumped into underground geologic formations, such as unminable coal beds, depleted oil or gas wells, or saline aquifers, in a process that is essentially the reverse of pumping oil up from below the earth's surface. Engineers are also looking into the possibility of bubbling carbon dioxide directly into the ocean at concentrations that will not affect the surrounding ecosystem and at depths that will ensure it remains in the ocean.

How will scientists make certain it is stored safely? Making sure carbon dioxide will be stored in a safe and environmentally sound manner is one of our primary goals. Memories of the 1986 Lake Nyos tragedy in Cameroon (in which a huge bubble of carbon dioxide erupted from the lake, suffocating some 1,700 people), raise the issue of safety, particularly for underwater storage. Yet the situation in the lake was entirely different than the scenario we envision for carbon sequestration in the ocean. A small lake simply cannot hold a large amount of carbon dioxide, so the Nyos eruption was inevitable. There are no such limitations in the oceans. In the case of underground storage, nature has demonstrated a safe track record: reservoirs such as the McElmo Dome in southwestern Colorado have held large quantities of carbon dioxide for centuries.

Are there any active carbon sequestration projects today? The Sleipner natural gas rig off the coast of Norway currently pumps carbon dioxide into a saline aquifer 1,000 meters below the seafloor. Although Sleipner is the only sequestration project driven solely by climatic change considerations, other commercial projects demonstrate the technology. More than a dozen power plants capture carbon dioxide from their flue gas, including the Shady Point, Okla., plant built by the international engineering company ABB. And at over 65 oil wells in the U.S., companies inject the gas underground to enhance the efficiency of oil drilling.



NATURAL STORES OF CARBON exist in the atmosphere, oceans, sediments and biosphere; exchange between these reservoirs occurs in a variety of ways. When humans burn fossil fuels, we transfer carbon originally stored in the deep sediments into the atmosphere. The goal of carbon sequestration is to redirect carbon from the atmosphere into one of the other three reservoirs.

depth. The cooler, denser water below travels extremely slowly up through the thermocline. Therefore, the water beneath the thermocline may take centuries to mix with the surface waters, and any carbon dioxide below this boundary will be effectively trapped. In general, the deeper we inject the carbon dioxide, the longer it will take to reach the atmosphere.

Carbon dioxide can be introduced into seawater in two ways: dissolving it at moderate depths (from 1,000 to 2,000 meters) to form a dilute solution or injecting it below 3,000 meters to create what we call a carbon dioxide lake. The first strategy seeks to minimize local environmental effects by diluting the carbon dioxide, whereas the lake approach tries to maximize the length of time the carbon dioxide will reside in the ocean.

The concept of storing carbon dioxide in the ocean can be traced to a 1977 paper by Cesare Marchetti of the International Institute for Applied Systems Analysis in Laxenburg, Austria, who suggested that carbon dioxide could be piped into the waters of the Mediterranean Sea at Gibraltar, where it would naturally flow out into the Atlantic and be carried to the deep ocean. Even today building a pipe along the ocean floor to transport carbon dioxide to an appropriate depth remains one of the more realistic options for carbon sequestration. Other injection scenarios that have been suggested include dropping dry ice into the ocean from ships, introducing carbon dioxide at 1,000 meters through a pipe towed by a moving ship, and running a pipe down 3,000 meters or more to depressions in the seafloor.

Safe and Sound?

Despite the availability of the technology necessary to proceed with carbon storage in both terrestrial and oceanic reservoirs, we need to understand better what the consequences for the environment will be. Obviously, the process of storing carbon dioxide needs to be less damaging to the environment than the continued release of the greenhouse gas. In the case of underground storage, we must be sure to assess the long-term stability of any formation under consideration as a reservoir. The structural integrity of a site is important not only to ensure that the gas does not return to the atmosphere gradually but also because a sudden release of the carbon dioxide in a populated area could be catastrophic. Carbon dioxide is heavier than air, and a rapid, massive discharge of the gas would displace oxygen at the surface, suffocating people and wildlife. Fortunately, though, nature has stored carbon dioxide underground for millions of years in reservoirs such as McElmo Dome in southwestern Colorado, so we know there are ways to do it safely.

Ocean sequestration presents a different set of challenges. The leading concern is the repercussion it will have on the acidity of the ocean. Depending on the method of carbon dioxide release, the pH of seawater in the vicinity of an injection site could be between 5 and 7. (A pH of 7 is considered neutral; the pH of seawater is normally around 8.)

A large change in acidity could be harmful to organisms such as zooplankton, bacteria and bottom-dwelling creatures that cannot swim to less acidic waters. Research by one of us (Herzog) and M.I.T. colleague E. Eric Adams, however, suggests that keeping the concentration of carbon dioxide dilute could minimize or even eliminate problems with acidity. For example, a dilution factor of one part per million yields a change in pH of less than 0.1. This reduced concentration could easily be achieved by releasing the carbon dioxide as small droplets from a pipe on the seafloor or on a moving ship.

Over the next several years, the scientific community will be conducting a number of experiments to assess how large amounts of carbon dioxide can be stored in a safe and environmentally sound manner. In the summer of 2001, for instance, a team of researchers from the U.S., Japan, Switzerland, Norway, Canada and Australia will begin a study off the Kona Coast of Hawaii to examine the technical feasibility and environmental effects of carbon storage in the ocean. (Two of us are participating in this project, Herzog as a member of the technical committee and Eliasson as a member of the steering committee.)

Our plan is to run a series of about 10 tests over a period of two weeks, involving the release of carbon dioxide at a depth of 800 meters. We will be monitoring the resulting plume and taking measurements, including the pH of the water and the amount of dissolved inorganic carbon. These data will allow us to refine computer models and thereby generalize the results of this experiment to predict environmental responses more accurately. We are also interested in what technical design works best to rapidly dilute the small droplets of carbon dioxide.

Money Matters

Along with questions of environmental safety and practicality, we must look at how much carbon sequestration will cost. Because electricity-generating power plants account for about one third of all carbon dioxide released to the atmosphere worldwide and because such plants are large, concentrated sources of emissions, they provide a logical target for implementing carbon sequestration. Furthermore, such plants have had experience reducing pollutants in the past. (Notably, though, attention has primarily focused on controlling such contaminants as particulate matter, sulfur oxides, nitrogen oxides or even carbon monoxide—but not on carbon dioxide itself.)

Devices known as electrostatic precipitators, first introduced in the 1910s, helped to clean up the particles emitted from burning fossil fuels while raising the price of electricity only modestly. Today a modern power plant that includes state-of-the-art environmental cleanup equipment for particulates, sulfur oxides and nitrogen oxides costs up to 30 percent more to install than a plant without such equipment. This environmental equipment adds only between 0.1 and 0.5 of a cent per kilowatt-hour to the price of the electricity generated.

Because the exhaust gases of fossil-fueled power plants contain low concentrations of carbon dioxide (typically ranging from 3 to 15 percent), it would not be economical to funnel the entire exhaust stream into storage sites. The first step, therefore, should be to concentrate the carbon dioxide found in emissions. Unfortunately, with existing equipment this step turns out to be the most expensive. Thus, developing technology that lowers these costs is a major goal.

The most common method for separating carbon dioxide involves mixing a solution of dilute monoethanolamine (MEA) with the flue gases inside the absorption tower of a plant designed to capture the greenhouse gas. The carbon dioxide in the exhaust reacts with the MEA solution at room temperature to form a new, loosely bound compound. This compound is then heated in a second column, the stripping tower, to approximately 120 degrees C to release the carbon dioxide. The gaseous carbon dioxide product is then compressed, dried, chilled, liquefied and purified (if necessary); the liquid MEA solution is recycled. Currently this technology works well, but it must become more energy-efficient if it is to be applied to large-scale carbon sequestration. Today only a handful of power plants, including one built in Shady Point, Okla., by ABB (where Eliasson serves as head of global change research), capture carbon dioxide from their flue gases. The carbon dioxide

PLANT A TREE

ANOTHER OPTION FOR STORING CARBON NEEDS ONLY SUN AND WATER

For over a decade, an organized carbon sequestration project has been under way in the deforested regions and farmlands of Guatemala. No underground pipes or pumping stations are required—just trees. As the plants grow, they absorb carbon dioxide from the atmosphere, which they store as carbon in the form of wood. Hoping to capitalize on this natural vehicle for sequestering carbon, companies and governments have initiated reforestation, afforestation (planting trees on land not previously forested) and agroforestry (integrating trees with agricultural crops) efforts as a way to meet obligations set forth in the Kyoto Protocol, the international environmental treaty on lowering greenhouse gas emissions.

In 1988 AES, a U.S.-based electrical company, pioneered the first forestry project designed to offset carbon dioxide emissions. At the time, AES was about to build a new coal-fired power plant in Connecticut, which was expected to release 52 million tons of carbon dioxide during its 40-year life span. Working in Guatemala with the World Resources Institute (WRI) and the relief organization CARE, AES created community woodlots, introduced agroforestry practices and trained forest-fire brigades. According to WRI calculations, up to 58 million tons of carbon dioxide will be absorbed over the lifetime of the project. Currently more than a dozen such programs are under way on some four million hectares of forest land, including areas in the U.S., Norway, Brazil, Malaysia, Russia and Australia.

SEEDLINGS are planted by workers in Fiji as part of a reforestation effort.

PETER ARNOLD, INC.

According to recent estimates, forests around the globe today store nearly one trillion tons of carbon. Scientists calculate that to balance current carbon dioxide emissions, people would have to plant new forests every year covering an area of land equivalent to the whole of India. Forestry projects are not a quick-fix solution, but they do offer many benefits, ranging from better habitats for wildlife to increased employment. Nevertheless, the potential for trees to serve as a reservoir for carbon is limited, and the approach has its drawbacks. Tree plantations drain native plant biodiversity and can disturb local communities, forcing them to relocate. As with many proposed solutions to climate change, trees will be effective only as one part of a global commitment to reduce greenhouse gas emissions. —*Diane Martindale*

A BREAKTHROUGH IN CLIMATE CHANGE POLICY?

BY DAVID W. KEITH AND EDWARD A. PARSON

As a result of human activities, the atmospheric concentration of carbon dioxide has increased by 31 percent over the past two centuries. According to business-as-usual projections, it will reach twice the preindustrial level before 2100. Although there is little doubt that this increase will noticeably transform the climate, substantial uncertainties remain about the magnitude, timing and regional patterns of climate change; even less is known about the ecological, economic and social consequences.

Despite these uncertainties, an international consensus has emerged regarding the importance of preventing runaway levels of carbon dioxide in the atmosphere. An effort to stabilize the concentration of carbon dioxide at even double its preindustrial level—generally considered the lowest plausible target—will require reducing global carbon dioxide emissions by about 50 percent from projected levels by 2050. Not surprisingly, such an extreme reduction will require a fundamental reorganization of global energy systems.

Most current assessments of greenhouse gas emissions assume that the reductions will be achieved through a mix of increasing energy efficiency and switching to nonfossil-fuel alternative energy sources, such as solar, wind, biomass or nuclear. In the accompanying article, "Capturing Greenhouse Gases," the authors review a radically different approach: burning fossil fuels without releasing carbon dioxide to the atmosphere by separating the carbon emissions and burying them underground or in the deep ocean. We believe this approach—termed carbon management—has fundamental implications for the economics and politics of climate change.

Stabilizing the carbon dioxide concentration at 550 parts per million (ppm)—double the preindustrial level—is widely considered an ambitious target for emissions control. Yet this concentration will still cause substantial climate change. The resulting environmental problems, however, will most likely have only a small effect on the world's overall economic output; rich countries in particular should emerge relatively unscathed. But the results for specific regions will be more pronounced, with some places benefiting and others suffering. For instance, although parts of the northern U.S. may enjoy warmer winters, entire ecosystems, such as the southwestern mountain forests, alpine meadows and certain coastal forests, may disappear from the continental U.S. These likely consequences—and more important, the possibility of unanticipated changes—are compelling reasons to try to stabilize concentrations below 550 ppm, if it can be done at an acceptable cost.

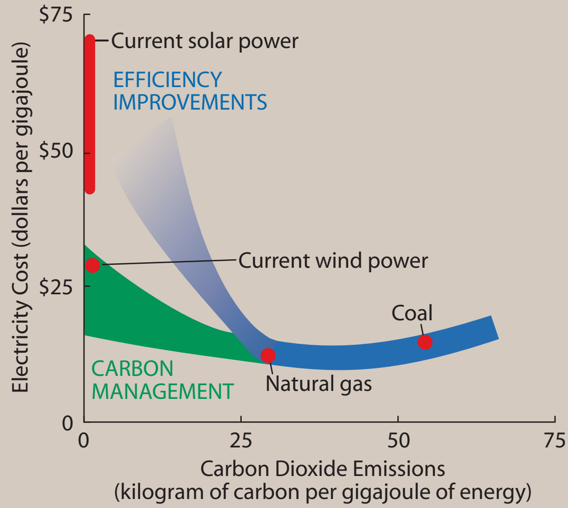
At present, the cost of holding concentrations to even 550 ppm through conventional means appears high, both in dollars and in other environmental problems. All nonfossil-fuel energy sources available today are expensive, and renewable sources have low power densities: they produce relatively little power for the amount of land required. Large-scale use of renewable energy could thereby harm our most precious environmental resource: land. Although technological advances should reduce the cost of renewables, little can be done to improve their power densities, which are intrinsic to the sources.

So must we conclude that reducing carbon emissions without causing other unacceptable environmental impacts will deliver a massive economic blow? Not necessarily. The crux of the cost problem is predicting how fast money-saving technical advances might develop in response to a carbon tax or some other form of regulation. Notably, most economic models used today to assess the cost of reducing emissions assume that innovation proceeds at its own pace and cannot be accelerated by policy. Under this assumption, delaying efforts to cut emissions makes sense because it will allow time to develop better technology that will lower the cost of reductions. Under the contrary assumption—which we regard as closer to the truth—innovation responds strongly to price and policy signals. In this case, early policy action on climate change is advantageous, because it would stimulate the innovations that reduce the cost of making large emission reductions.

Carbon management may be just such an innovation. Certain carbon management technologies are already available and appear to be significantly cheaper than renewables for generating electricity. To achieve deep reductions in greenhouse gas emissions, however, society must also start using carbon-free fuels, such as hydrogen, for transportation. Here the relative advantage of carbon management over renewables is even greater than in producing electricity. Furthermore, these technologies offer one significant advantage over alternative energy sources: because they are more compatible with the existing energy infrastructure, we expect their costs to fall more quickly than those of renewables.

Carbon management weakens the link between burning fossil fuels and releasing greenhouse gases, making the world's economic dependence on fossil fuels more sustainable. This gives carbon management a crucial advantage: by reducing the threat to fossil-fuel industries and fossil-fuel-rich nations, carbon management may ease current political deadlocks. Stated bluntly, if society adopts carbon management widely, existing fossil-fuel-dependent industries and nations may continue to operate profitably both in present energy markets and in new

Costs of Reducing Carbon



DAVID FIERSTEIN

REDUCING CARBON DIOXIDE EMISSIONS by switching from coal to natural gas can save money. The authors argue that further reductions will be cheaper to make by carbon management (*green*) than by solar power or by extreme efficiency improvements (*blue*). Although wind power is relatively cheap, the land area required may preclude its widespread use.

markets that develop around carbon management, making them more willing to tolerate policies that pursue substantial reduction of atmospheric emissions.

Environmentalists, however, are likely to find carbon management profoundly divisive for several reasons. Carbon sequestration is only as good as the reservoirs in which the carbon is stored. The unfortunate history of toxic and nuclear waste disposal has left many reasonable people skeptical of expert claims about the longevity of underground carbon disposal. As researchers assess the safety of proposed carbon reservoirs both underground and in the ocean, they must address such skepticism evenhandedly.

Perhaps even more disconcerting for environmentalists, though, is that carbon management collides with a deeply rooted belief that continued dependence on fossil fuels is an intrinsic problem, for which the only acceptable solution is renewable energy. Carbon management was first proposed as "geoengineering," a label it now shares with proposals to engineer the global climate, for example, by injecting aerosols into the stratosphere to reflect solar radiation and cool the earth's surface. Many environmentalists hold a reasonable distaste for large-scale technical fixes, arguing that it would be better to use energy sources that do not require such massive clean-up efforts.

Carbon management is a promising technology, but it remains unproved. And caution is certainly wise: the history of energy technologies is littered with options once touted as saviors that now play at most minor roles (for example, nuclear energy). Exploring the potential of either carbon management or renewable energy will require political and economic action now—that is, greater support for basic energy research and carbon taxes or equivalent policy measures that give firms incentives to develop and commercialize innovations that reduce emissions at a reasonable cost. It may be that carbon management will allow the world—at long last—to make deep cuts in carbon dioxide emissions at a politically acceptable cost. Indeed, for the next several decades, carbon management may be our best shot at protecting the global climate.

DAVID W. KEITH and EDWARD A. PARSON often collaborate on environmental policy research. Keith is an assistant professor in the department of engineering and public policy at Carnegie Mellon University. Parson is an associate professor at the John F. Kennedy School of Government at Harvard University.

is then sold for commercial applications, such as freeze-drying chicken or carbonating beer and soda.

Another application for captured carbon dioxide offers a number of possible benefits. Methanol can be used as fuel even now. Generating this cleaner source of energy from captured carbon dioxide and hydrogen extracted from carbon-free sources would be more expensive than producing methanol from natural gas, as is currently done. But by reusing carbon dioxide—and by giving it a market value—this procedure ought to reduce overall emissions, provide an incentive to lower the costs of carbon dioxide–capture technology and help start a transition to more routine use of cleaner fuels.

Scientists, policymakers and the public must deal with the continuing importance of coal, oil and natural gas as a source of energy, even in a world constrained by concerns about climate change. The basic technology needed to use these fuels in a climate-friendly manner does exist. Current equipment for capturing carbon dioxide from power plants would raise the cost of generating electricity by 50 to 100 percent. But because sequestration does not affect the cost of electricity transmission and distribution (a significant portion of consumers' electricity bills), delivered prices will rise less, by about 30 to 50 percent. Research into better separation technologies should lead to lowered costs.

ABB CORPORATE RESEARCH

CAPTURE PLANT located in Shady Point, Okla., separates carbon dioxide from its exhaust fumes; the gas is then sold for use in the food industry.

What needs to happen for carbon sequestration to become common practice? First, researchers need to verify the feasibility of the various proposed storage sites, in an open and publicly acceptable process. Second, we need leadership from industry and government to demonstrate these technologies on a large enough scale. Finally, we need improved technology to reduce costs associated with carbon dioxide separation from power plants. The Sleipner project has shown that carbon sequestration represents a realistic option to reduce carbon dioxide emissions when an economic incentive exists. During the past 100 years, our energy supply system has undergone revolutionary changes—from a stationary economy based on coal and steam to a mobile economy based on liquid fuels, gas and electricity. The changes over the next 100 years promise to be no less revolutionary. SA

The Authors

HOWARD HERZOG, BALDUR ELIASSON and OLAV KAARSTAD met in Amsterdam in March 1992 at the First International Conference on Carbon Dioxide Removal. Herzog, a principal research engineer at the Massachusetts Institute of Technology Energy Laboratory, is the primary author of a 1997 U.S. Department of Energy White Paper on carbon sequestration. Eliasson, head of ABB's Energy and Global Change Program, is the Swiss representative to as well as vice chairman of the International Energy Agency's Greenhouse Gas Research and Development Program. Kaarstad, principal research adviser in the area of energy and environment at the Norwegian oil and gas company Statoil, is currently involved in the ongoing carbon dioxide–injection project at the Sleipner field in the North Sea.

Further Information

ABB Group's Energy and Global Change Web site is at www.abb.com/ (click on "Environment," then on "Energy and Global Change").

IEA Greenhouse Gas Research and Development Program Web site is at www.ieagreen.org.uk/

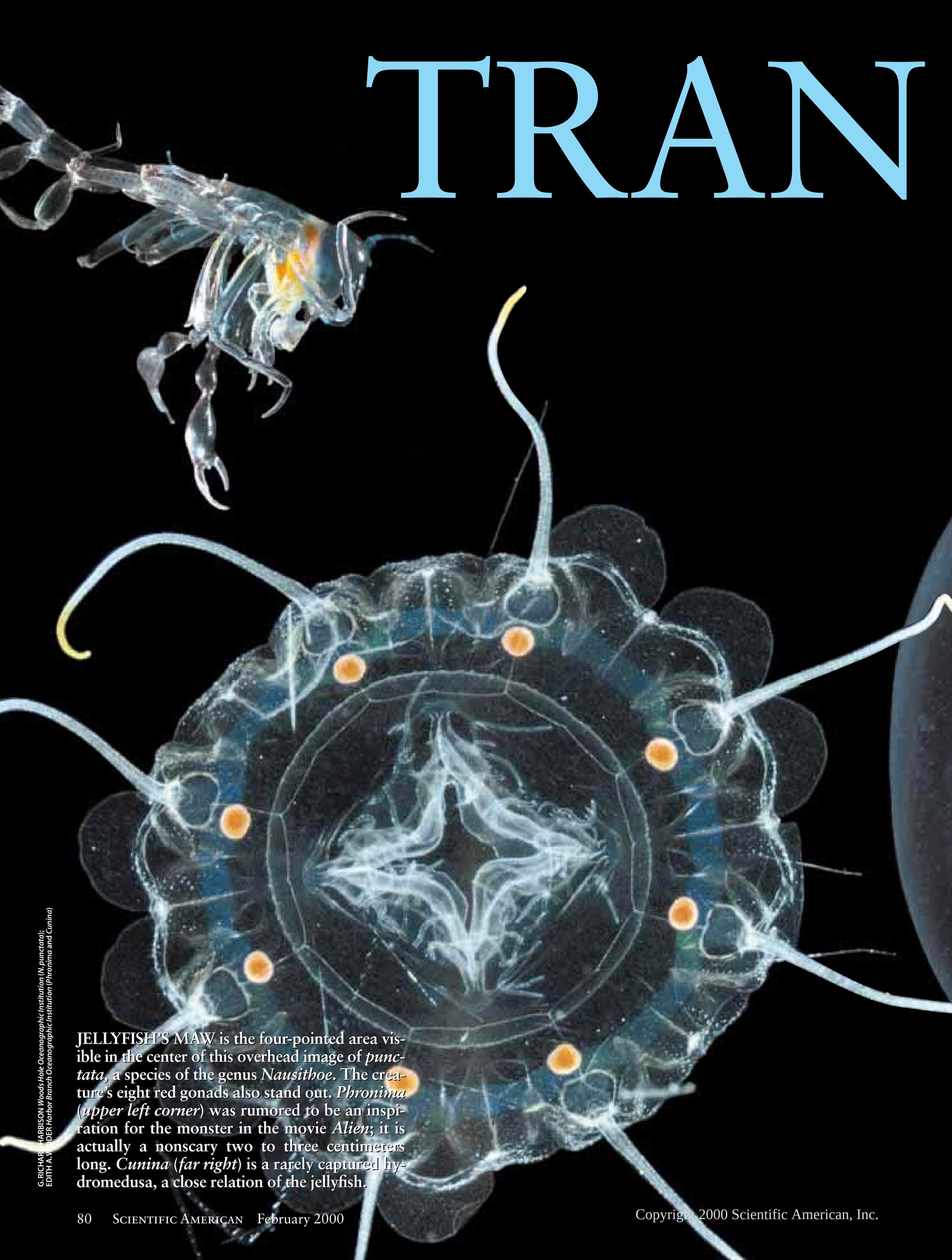
M.I.T. Energy Laboratory Web site is at web.mit.edu/energylab/www

Statoil Web site is at www.statoil.com (for information on the Sleipner area in particular, go to www.statoil.com/statoilcom/svg00990.nsf/ealias/Sleipner).

U.S. Department of Energy's Office of Fossil Energy Web site is at www.fe.doe.gov/coal_power/sequestration/

U.S. Department of Energy's Office of Science Web site is at www.sc.doe.gov/production/ober/carbseq.html

TRAN



JELLYFISH'S MAW is the four-pointed area visible in the center of this overhead image of *punctata,* a species of the genus *Nausithoe.* The creature's eight red gonads also stand out. *Phronima* (*upper left corner*) was rumored to be an inspiration for the monster in the movie *Alien*; it is actually a nonscary two to three centimeters long. *Cunina* (*far right*) is a rarely captured hydromedusa, a close relation of the jellyfish.

G. RICHARD HARBISON *Woods Hole Oceanographic Institution (N. punctata);* EDITH A. WIDDER *Harbor Branch Oceanographic Institution (Phronima and Cunina)*

SPARENT *Animals*

by Sönke Johnsen

Ingenious physiological accommodations have evolved to enable a stunning variety of undersea creatures to be remarkably transparent

Story begins on page 87

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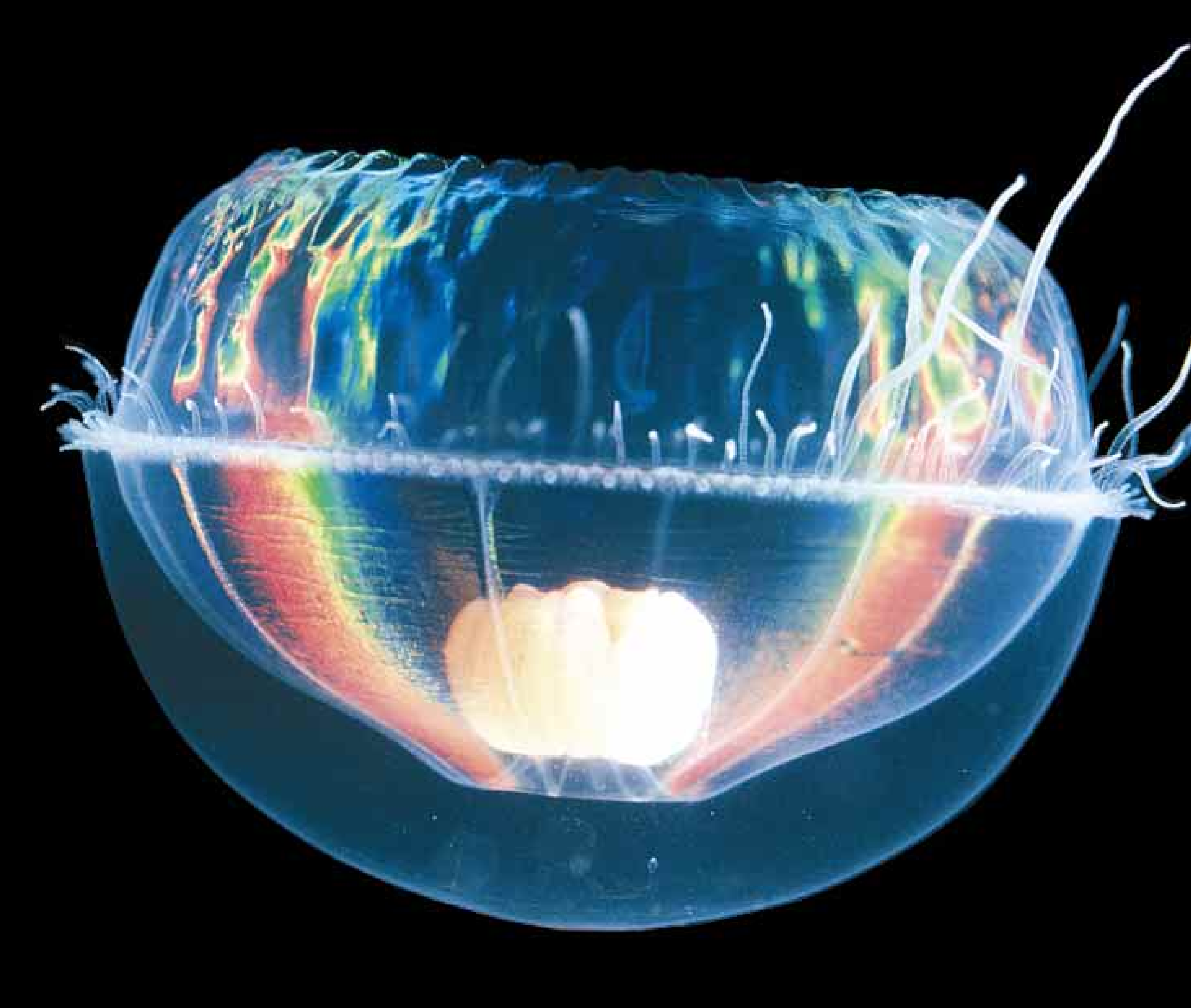


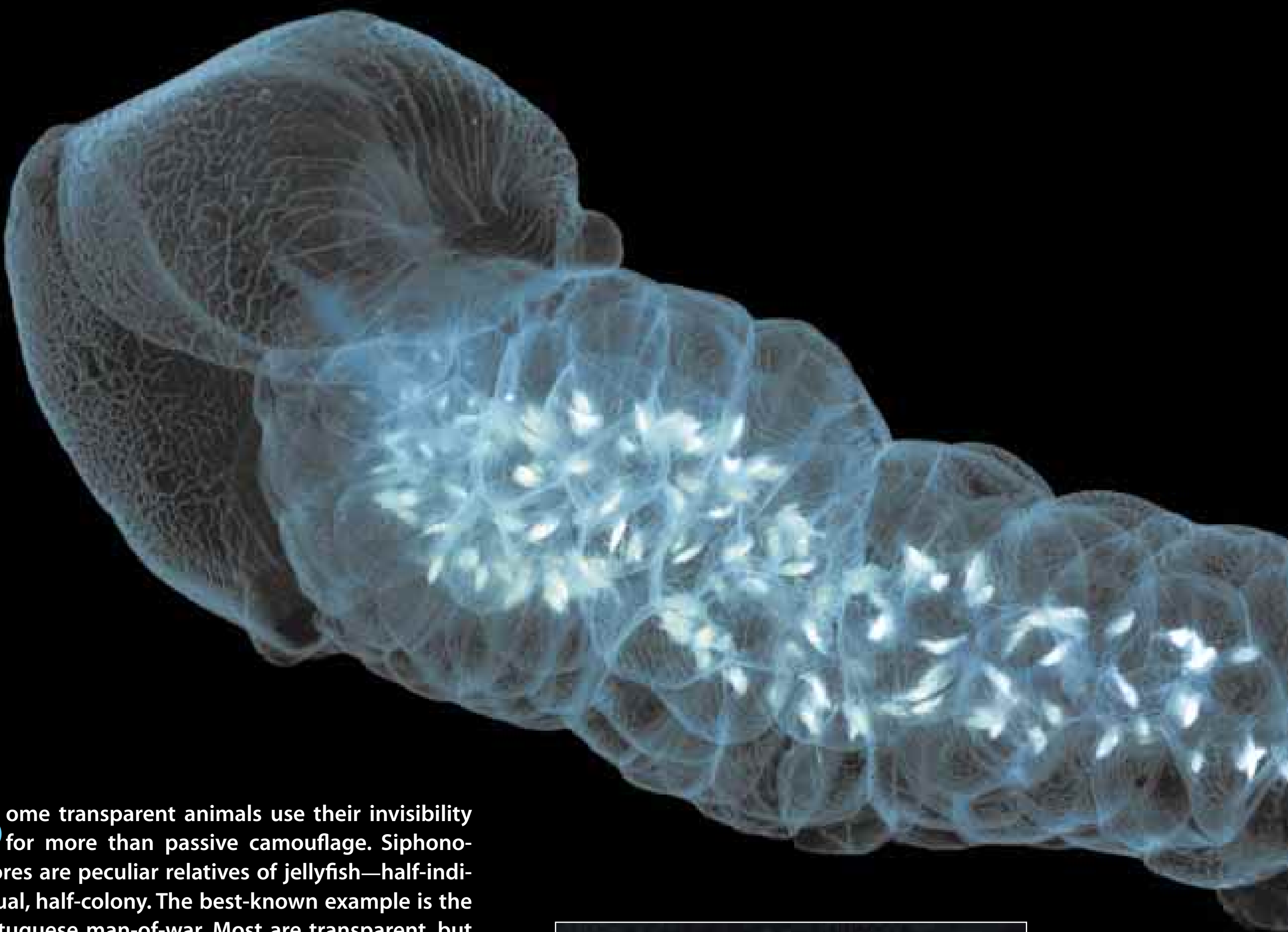
LAURENCE P. MADIN *WHOI* (*Arctapodema*); G. RICHARD HARBISON (*Pterosoma* and *Ctenophora*)

Glasslike Menagerie

Flamelike, iridescent colors appeared on a hydromedusa of the genus *Arctapodema* (*large image at left*) when the light from the photographer's strobe shone on fine muscle striations on the animal's body. The transparent snail *Pterosoma* (*lower left corner*) has an elongated retina that takes in images line by line, like a television camera. The photograph next to it shows a creature so recently discovered that it has not yet been named. It is a comb jelly, of the phylum Ctenophora, which paddles through the water by moving the comb plates along the edges of its body. The amphipod below, known as *Cystosoma*, resembles a five-centimeter-long crystalline roach. Its exterior shell encloses mostly water, as well as a tiny, needlelike vertical gut that is not visible in this image. This transparent octopus, *Vitreledonella richardi* (*right*), is also rarely captured and little known.

EDITH A. WIDDER (*Cystosoma*); G. RICHARD HARBISON (*Vitreledonella richardi*)

Siphonophores: One's a Crowd



EDITH A. WIDDER

Some transparent animals use their invisibility for more than passive camouflage. Siphonophores are peculiar relatives of jellyfish—half-individual, half-colony. The best-known example is the Portuguese man-of-war. Most are transparent, but some have colorful stinging organs that mimic the appearance of baby fish, small shrimp and other alluring prey. Animals pursue these organs, unaware of the much larger transparent animal they are attached to, and are quickly killed. Above, a creature of the taxonomic group prayid is shown in a compressed state, only about 10 or 12 centimeters long. The light-colored objects inside it are stinging cells. In hunting mode the animal transforms itself, stretching out to a meter in length, with the stinging cells dangling, netlike, off buoyant organs. Another siphonophore, *Forskalea* (*right*), is a close relative of the Portuguese man-of-war; it hunts in much the same way as the prayid does.

G. RICHARD HARBISON

Polarization: The Predator's Secret Weapon

NADAV SHASHAR *H. Steinitz Marine Biology Laboratory* (copepods)

In the continual arms race between the eaters and the eaten, some predators have developed a way to counter the camouflage of transparency. In the ocean, water molecules scatter much of the light, creating polarized light, whose light waves oscillate in parallel. People can discern polarized light only if they are wearing Polaroid sunglasses, but many animals, especially crustaceans and squid, can see such light with their unaided eyes. That capability aids their hunting because the tissues of some of the transparent animals they prey on either remove or rotate the polarization of the light that passes through them. Detecting such a change thus enables the predators to sense the presence of their prey. In the photographs of the same *Labidocera* copepod (*above*), the one at the right shows the creature as it would be seen by eyes that can detect a change in polarization.

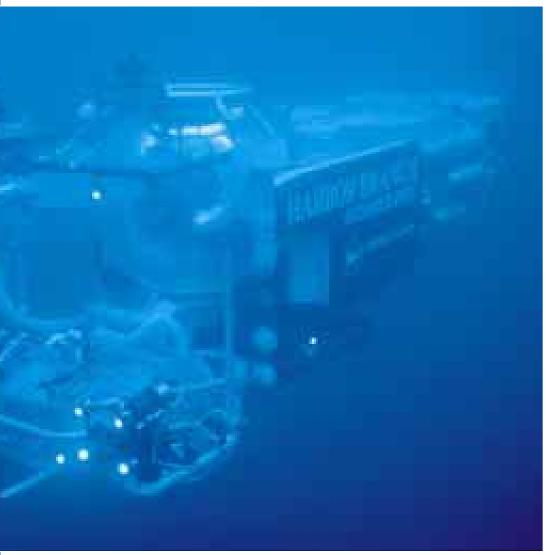
Recently Nadav Shashar and his colleagues at the Marine Biological Laboratories in Woods Hole, Mass., have shown that squid use their ability to see polarization to find transparent food and to send secret signals to one another. Shashar, now at the H. Steinitz Marine Biology Laboratory in Eilat, Israel, gave squid a choice of two glass beads to attack. One of the beads affected the polarization of the light; the other did not. He found that the squid preferred to attack the beads that did affect the light's polarization. Shashar also found that under polarized illumination—the natural state of light in the ocean—the squid were able to detect, at a longer range, creatures that affected polarization.

LAURENCE P. MADIN

HARBOR BRANCH OCEANOGRAPHIC INSTITUTION

VENUS'S GIRDLE, a species of comb jelly, drifts in front of diver Neil Swanberg off Bimini, a Bahamian island. The animal, just millimeters thick but up to two meters long, is obviously too big for the specimen jar Swanberg brought along on the dive. Common methods of collecting sea creatures, such as the use of towed nets, leave a mangled mass of tissue (*inset, above left*) if applied to transparent animals. So within about 30 meters of the surface, divers hand-collect specimens; at greater depths, biologists rely on research submersibles such as the *Johnson Sea-Link* (*inset, above right*). The submersible is equipped with jars that can be opened and closed remotely using hydraulics.

Below us yawns the abyss, more than 3,000 meters deep.



AL GIDDINGS IMAGES UNLIMITED

Except for the small launch boat I am sitting in and the white mother ship in the distance, there is nothing but sea and sky. Taking a breath from my scuba regulator, I roll over the side of the launch into water so clear and empty that I can see for almost 100 meters. As I descend with three of my colleagues, the blue of the water darkens around us to a medium cobalt that deepens to purple as we face downward.

Hundreds of kilometers from land, we are dropping down not to a thriving reef or some storied shipwreck but rather to a point arbitrarily chosen in the open ocean. Below us yawns the abyss, more than 3,000 meters deep. We are in the earth's largest habitat, which occupies more than 99 percent of the planet's livable space. It is a featureless world, where only the gentlest gradations of light and color signal a change in time or space.

For us, the lack of reference is profoundly disorienting. For the animals that live here, it means there is no place to hide.

At 18 meters we stop our descent, clip on to a safety line dangling from the launch and begin our search. We do not have to look far: as our eyes adjust, we find we are surrounded by dozens of slow-moving, transparent animals. In this exotic glass menagerie there are a few jellyfish, but most of the creatures are not immediately recognizable. They range from thumb size to bigger than a basketball, and whereas some are revealed by the food in their stomachs or by the occasional color spot or flash of iridescence, others are so clear that they are invisible even centimeters away. We pull glass jars from our net bags and begin collecting.

Gelatinous Life

What most of these creatures have in common are bodies that consist largely of a gelatinous material, which bestows numerous benefits. Because this substance is mostly incompressible water, the animals are protected from the crushing pressure of the deep. It has just enough buoyancy to allow many of them to float like balloons over the abyss. The material is also nonliving and easy to produce, so creatures made of it can live on very little food. When food is abundant, they can grow and reproduce at phenomenal rates, some blooming—in a single week—into colonies of billions of individuals covering thousands of square kilometers.

Perhaps the most important advantage of gelatinous material—and the foundation for its evolutionary success in the undersea realm—is the transparency it can confer: almost all open-ocean animals not otherwise protected by teeth, toxins, speed or small size have some degree of invisibility. In fact, transparency is uncommon only at depths where sunlight never penetrates.

The drawback is that gelatinous animals are delicate and slow. Quite a few of them rely almost completely on invisibility, the ultimate form of camouflage, to elude their predators and to stalk their own prey.

Its importance in the marine environment notwithstanding, transparency is still a largely mysterious characteristic. Thus, my own research has focused on fairly basic questions, such as: How clear can these animals be? And what unusual physiological characteristics enable the creatures to achieve high levels of transparency?

The first step in understanding the ecology of transparency is determining how transparent the animals really are. In that endeavor, the most difficult aspect is capturing them in good condition. They are typically transparent only when alive and healthy and turn opaque very quickly after dying. Catching healthy animals is difficult because they are so fragile; some can be torn apart by the turbulence from the near-by swish of a fish's tail. For that reason, the standard techniques for gathering gelatinous animals depend on scuba divers and submersibles.

Using both techniques, my colleagues and I have collected a wide variety of transparent animals in essentially perfect condition. Then, in a laboratory on the research vessel, I have measured the creatures' transparency across the visible spectrum using a spectrometer based on those that ophthalmologists use to measure the transparency of the human eye.

The animals' transparency varied over a range much greater than would be guessed from a quick visual estimation. The amount of light that passed through their bodies ranged from 20 to 90 percent. Not surprisingly, larger animals with more tissue compensated by having clearer tissue. More shocking was our finding that animals caught at 750 meters were just as transparent as those caught near the surface.

That observation puzzled me; I had expected that those near the surface would be more transparent because the surface world is brighter and harder to hide in. But it turned out that some of the deeper animals were more transparent than was necessary for them to be invisible just centimeters or even millimeters away from their predators' eyes.

To understand how a creature could be so transparent, consider that the visibility of an object depends on its contrast—its brightness compared with that of its surroundings. For a marine creature, the water between the animal and its observer scatters and absorbs the light reflected off the creature. So the farther away an animal is, the less contrast its image has and the harder it is to see. At some distance, depending on the animal's original contrast and how much the water affects the light, the contrast drops below what the observer can see. This distance is known as the sighting distance, and beyond it the animal is invisible (and safe).

Transparency and Structure

Unlike other forms of camouflage, transparency involves the entire body, not just its exterior. That fact presents several fascinating problems that evolution has solved in ingenious ways.

Some solutions can be seen by the naked eye. Some of these creatures are flat and thin, because thinner objects pass more light. If a centimeter of transparent snail lets through one ninth of the light, half a centimeter lets through one third. Flatness also makes the animal hard to see edge-on. Some, such as the fish larva called a leptocephalus, have taken this trick to extremes and are like living wafers, just a millimeter or two thick and tens of centimeters long. Certain comb jellies with the romantically evocative common name "Venus's girdle" are as long and flat as belts. And the young of Caribbean spiny lobsters are about as big as a half-dollar and as flat as paper. About the only way to detect them is to catch a fleeting glimpse of their shadow.

The other obvious changes involve parts that for physical reasons cannot be made transparent. Because retinas have to absorb light to see, at least a part of the eyes is always visible. Three solutions have emerged to this problem. Some organisms have their eyes on the ends of long stalks to distance them as much as possible. Others, such as the crustacean *Phronima* [*see illustration on page 80*], have extremely compact retinas and use natural conduits, like fiber optic cables, to channel the light to them. Still others, such as the large crustacean *Cystosoma* [*see illustration on page 83*], have huge eyes with very thin, pale retinas just under the cornea.

The stomach is another invariably visible organ. The reason is not the stomach itself, but its contents: partly digested animals or vegetation, which is typically opaque. In some see-through animals, however, the stomach is needle-shaped and always points down, no matter which way the animal is oriented. The arrangement can be effective because many predators search for their prey by looking up for shadows against the light from the ocean surface. Another strategy is to cloak the stomach in reflective tissue. In the open ocean such tissue, like a mirror, is invisible, because the light it reflects is indistinguishable from the light behind it. The same principle, incidentally, explains why so many fish have silvery, mirrorlike scales on the outside of their bodies.

Skin is the third troublesome organ because it always reflects at least some light. Some animals get by with simple body shapes that reduce the amount of skin and the complexity of the reflections. Less commonly but more intriguingly, some creatures have a microscopically bumpy texture on the surface of their bodies, which minimizes reflectivity in a way that is at once fascinating and subtle.

This strategy was the subject of a recent paper by Andrew Parker of the Australian Museum in Sydney. It depends on the refractive index of the material, which indicates how fast light travels through a material. Light travels more slowly in a material with a high refractive index than in one with a low index.

If a surface has a large number of bumps that are smaller than half the wavelength of the light falling on them, the whole surface acts like a uniform substance with a refractive index that is the average of the bumps and the surrounding medium (water, for our purposes). Because the bumps are larger at the bottom than at the top, however, the refractive index at the bottom is closer to that of the material—which is typically higher than that of water. For the same reason, the index is lower near the top of the bumps.

Thus, there is a gentle, rather than abrupt, increase in refractive index from the surrounding water to the body of the animal. That gentle transition reduces reflection; in fact, it works so well that lens designers are now using the principle to improve lens coatings in high-performance optics. It is also reportedly employed by Northrop Grumman in its B-2 stealth bomber to minimize the radar reflections from the aircraft's surface.

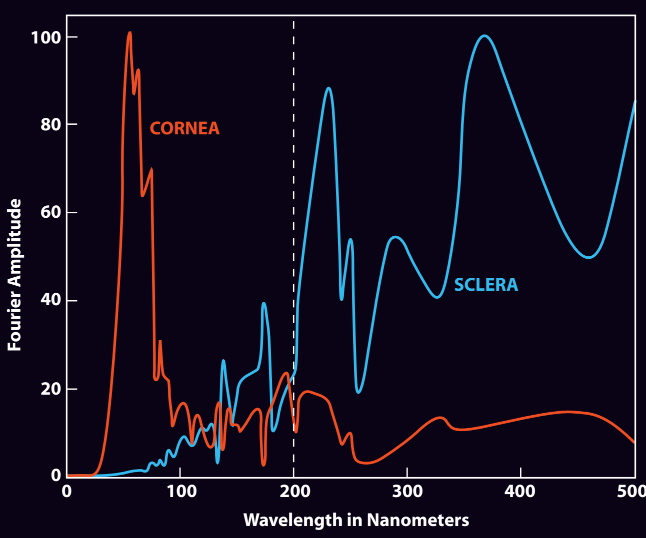
Requirements for Invisibility

Keeping reflections to a minimum is necessary but not sufficient for invisibility. Light must also pass unimpeded through the body, which requires that the beams are neither scattered nor absorbed as they travel through. Either

Why the Cornea Is Clear

Fourier analysis, which determines the predominant frequencies in a collection of waves or other repeating phenomena, has turned out to be extremely useful in analyzing transparency not only in gelatinous animals but also in the human cornea. Like the animals' bodies, the cornea and the surrounding white of the eye consist of periodic or semiregular arrangements of fibrous proteins. When these fibers are neatly ordered and spaced out with a "wavelength" less than half that of the shortest wavelength of visible light, the tissue approaches perfect transparency. The reason is that light passing directly through the tissue constructively reinforces itself, whereas light scattering off to the sides is eliminated by destructive interference.

This graph shows data I collected for both the cornea and the white of the eye (the sclera). In both cases, the fibers of the tissue exist in a variety of repeating patterns, each with a different wavelength. These wavelengths are plotted on the X axis. The predominance of a tissue with a certain wavelength is indicated by its corresponding value on the Y axis. In the cornea, for example, fibers repeating in a pattern with a wavelength of about 50 nanometers predominate. That value is well below 200 nanometers, which is about half the wave-



LAURIE GRACE

length of violet light, the shortest the human eye can see. In contrast, the sclera has peaks above 200 nanometers, rendering it opaque. —*S.J.*

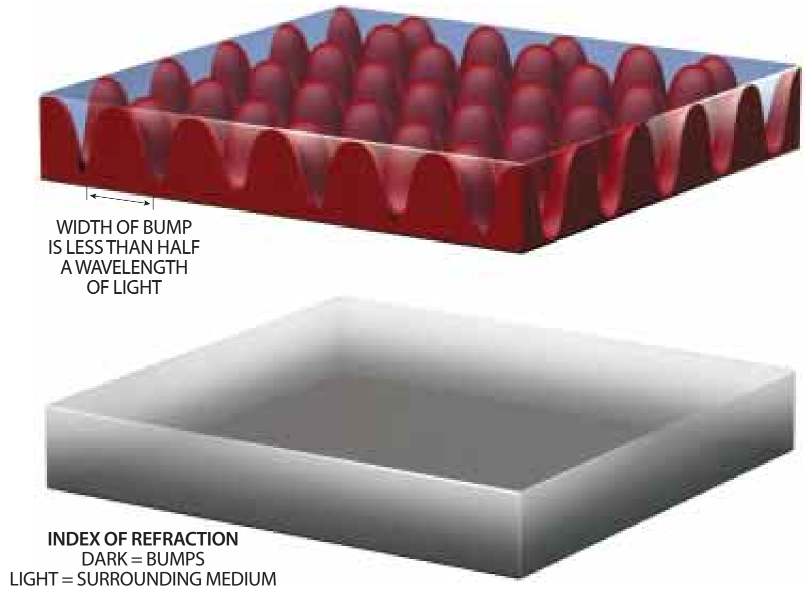
phenomenon would render the body more visible, but of the two, scattering is the more significant barrier to animal transparency because very few organic molecules absorb light.

Scattering is caused by variations in refractive index. As light passes from one material to another, a change in refractive index alters the light's speed. In addition, unless the light beam enters the new material perfectly perpendicularly, the direction of the beam changes.

Animal tissue normally has many variations in refractive index because of the diverse components required for life (cells, fibers, nuclei, nerves and so on). Even gelatinous animals, which contain a relatively large amount of water, have refractive index variations. The relation between refractive index variation and light scattering is extraordinarily complicated, and we do not know the details about the refractive index distribution inside living tissue.

Nevertheless, using simplified models and the assumption that tissue needs certain volumes of different components to survive, I examined how the size, shape and refractive index of these components affect the total amount of light scattering. Developers of house paints use similar methods to maximize the light scattering and therefore the hiding power of their paints.

The most important factors were the distribution and size of the components. If a cell requires a certain volume of fat to survive but must scatter as little light as possible, the best strategy is to divide the fat into a large number of very small droplets. A slightly worse strategy is to divide it into a few large droplets, and the worst strategy by many orders of magnitude is to divide the fat into drops about the size of the wavelength of light. The refractive index of the fat is less important; the shape of the droplets is least important. These factors provide a guide to what to look for in the microscopic anatomy of transparent animals.



DAVID FIERSTEIN

TINY BUMPS on the outside of a transparent creature's body can enhance invisibility by reducing reflections. Bumps with widths less than half the wavelength of the light falling on them do not have a distinct refractive index; rather the refractive index is the average of the bumps' index and that of the surrounding medium. But because the bumps are gently tapered, there is more of the material at the bottom than at the top. Thus, the refractive index shifts smoothly from that of the material to that of the medium. That gradual shift interferes with the ability of the bumpy surface to reflect light.

Refractive index variations do not always cause scattering, however. If the sizes of the refractive index variations are all smaller than half the wavelength of light, the scattered light from all the variations is eliminated by destructive interference. In destructive interference, light waves overlap in such a way that they cancel one another out.

For instance, the white and the cornea of the eye are both made of dense layers of collagen fibers, but because the fibers of the cornea are smaller and more tidily packed, the refractive index variations are all smaller than half the wavelength of light [*see box on opposite page*]. Therefore, there is strong destructive interference, and the organ is transparent. Without this interference, the cornea would be completely opaque. Cataracts arise when, in old age, this uniform packing of fibers becomes disturbed, throwing off their destructive interference.

Transparency is an extraordinary example of evolution in response to difficult circumstances. Through clever modifications of their bodies and cells, these delicate animals have found a way to survive in an exposed and dangerous environment. As is so often true, their naturally evolved methods rival the latest technological breakthroughs—in this case, in fiber optics, antireflection optical coatings and house paints. Their study is relevant to cataract research and to the expanding field of diagnosis and treatment of skin diseases with light. These animals, so common and yet so mysterious, have surprising things to teach us. SA

The Author

SÖNKE JOHNSEN entered biology with a background in mathematics and art, attracted to the subject by the beauty and mathematical elegance of animal forms. As a researcher at the Woods Hole Oceanographic Institution on Cape Cod, Mass., he focuses on all aspects of light in marine biology, including vision, bioluminescence, and the effects of ultraviolet radiation and magnetic fields.

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Uprooting the Tree of Life

About 10 years ago scientists finally worked out the basic outline of how modern life-forms evolved. Now parts of their tidy scheme are unraveling

by W. Ford Doolittle

Charles Darwin contended more than a century ago that all modern species diverged from a more limited set of ancestral groups, which themselves evolved from still fewer progenitors and so on back to the beginning of life. In principle, then, the relationships among all living and extinct organisms could be represented as a single genealogical tree.

Most contemporary researchers agree. Many would even argue that the general features of this tree are already known, all the way down to the root—a solitary cell, termed life's last universal common ancestor, that lived roughly 3.5 to 3.8 billion years ago. The consensus view did not come easily but has been widely accepted for more than a decade.

Yet ill winds are blowing. To everyone's surprise, discoveries made in the past few years have begun to cast serious doubt on some aspects of the tree, especially on the depiction of the relationships near the root.

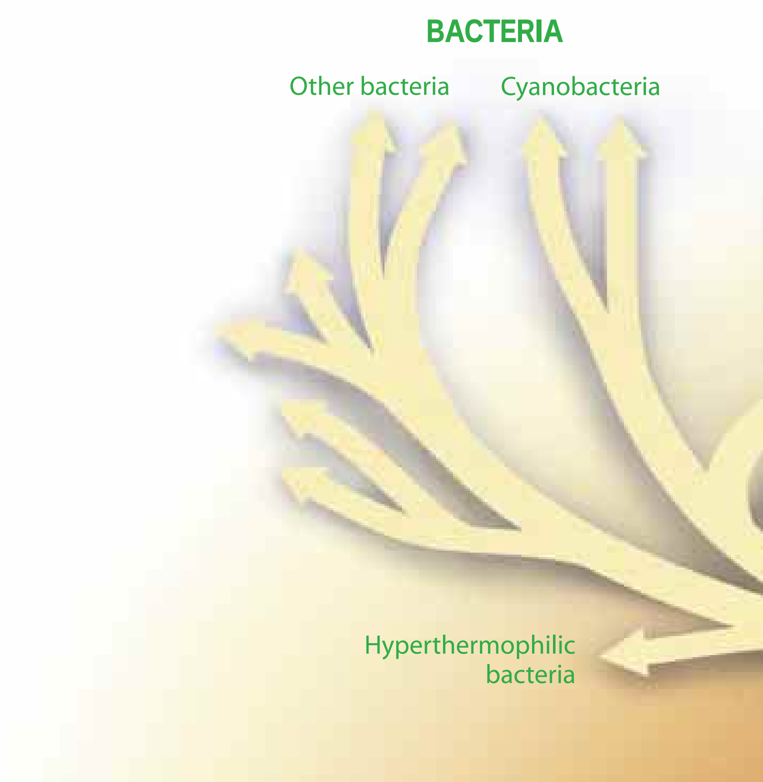
The First Sketches

Scientists could not even begin to contemplate constructing a universal tree until about 35 years ago. From the time of Aristotle to the 1960s, researchers deduced the relatedness of organisms by comparing their anatomy or physiology, or both. For complex organisms, they were frequently able to draw reasonable genealogical inferences in this way. Detailed analyses of innumerable traits suggested, for instance, that hominids shared a common ancestor with apes, that this common ancestor shared an earlier one with monkeys, and that *that* precursor shared an even earlier forebear with prosimians, and so forth.

Microscopic single-celled organisms, however, often provided too little information for defining relationships. That paucity was disturbing because microbes were the only inhabitants of the earth for the first half to two thirds of the planet's history; the absence of a clear phylogeny (family tree) for microorganisms left scientists unsure about the sequence in which some of the most radical innovations in cellular structure and function occurred. For example, between the birth of the first cell and the appearance of multicellular fungi, plants and animals, cells grew bigger and more complex, gained a nucleus and a cytoskeleton (internal scaffolding), and found a way to eat other cells.

In the mid-1960s Emile Zuckerkandl and Linus Pauling of the California Institute of Technology conceived of a revolutionary strategy that could supply the missing information. Instead of looking just at anatomy or physiology, they asked, why not base family trees on differences in the order of the building blocks in selected genes or proteins?

Their approach, known as molecular phylogeny, is eminently logical. Individual genes, composed of unique sequences of nucleotides, typically serve as the blueprints for making specific proteins, which consist of particular strings of amino acids. All genes, however, mutate (change in sequence), sometimes altering the encoded protein. Genetic mutations that have no effect on protein function or that improve it will inevitably accumulate over time. Thus, as two species diverge from an ancestor, the sequences of the genes they share will also diverge. And as time passes, the genetic divergence will increase. Investigators can therefore recon-



CONSENSUS VIEW of the universal tree of life holds that the early descendants of life's last universal common ancestor—a small cell with no nucleus—divided into two prokaryotic (non-nucleated) groups: the bacteria and the archaea. Later, the archaea gave rise to organisms having complex cells containing a nucleus: the eukaryotes. Eukaryotes gained valuable energy-generating organelles—mitochondria and, in the case of plants, chloroplasts—by taking up, and retaining, certain bacteria.

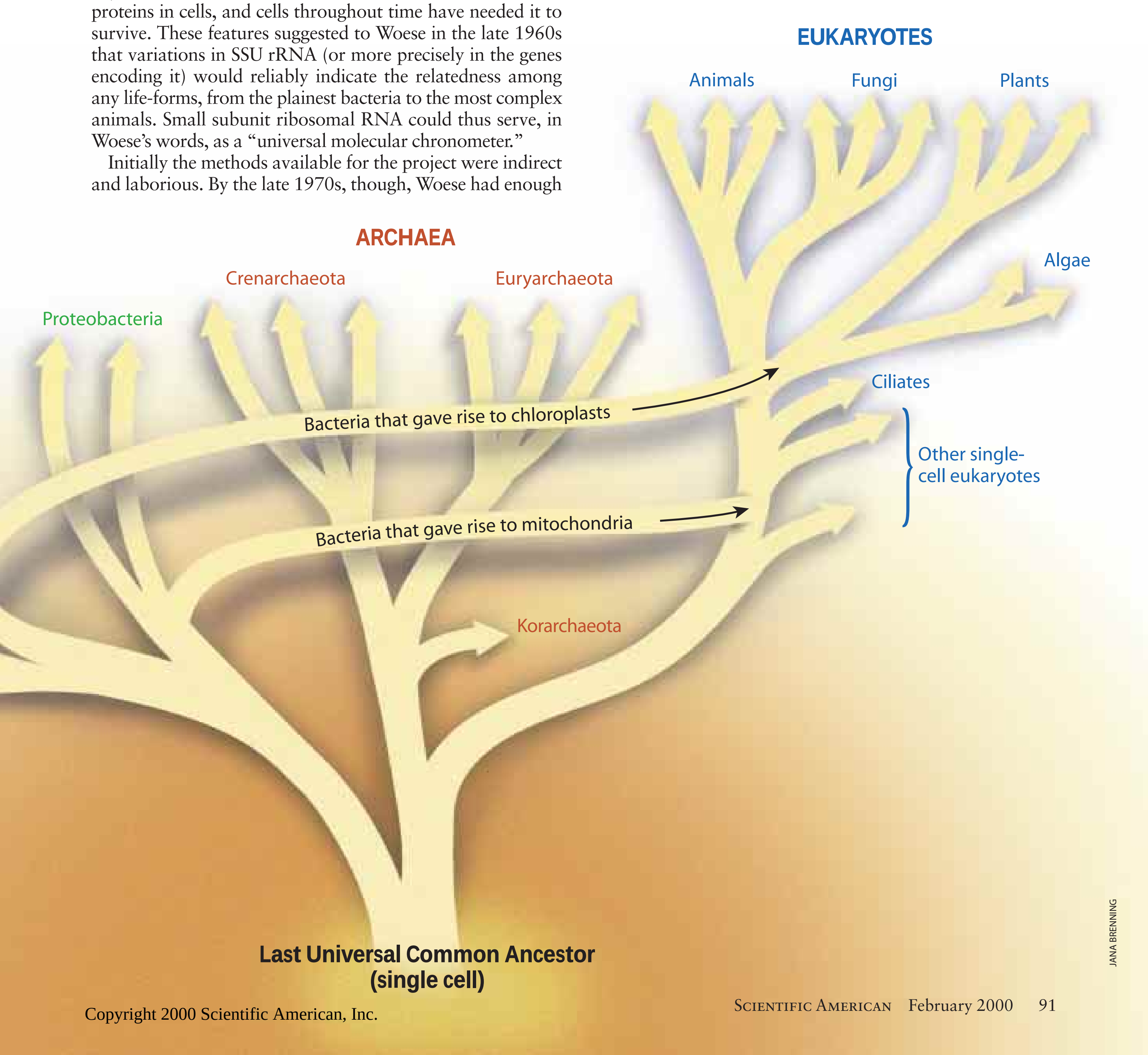
struct the evolutionary past of living species—can construct their phylogenetic trees—by assessing the sequence divergence of genes or proteins isolated from those organisms.

Thirty-five years ago scientists were just becoming proficient at identifying the order of amino acids in proteins and could not yet sequence genes. Protein studies completed in the 1960s and 1970s demonstrated the general utility of molecular phylogeny by confirming and then extending the family trees of well-studied groups such as the vertebrates. They also lent support to some hypotheses about the links among certain bacteria—showing, for instance, that bacteria capable of producing oxygen during photosynthesis form a group of their own (cyanobacteria).

As this protein work was progressing, Carl R. Woese of the University of Illinois was turning his attention to a powerful new yardstick of evolutionary distances: small subunit ribosomal RNA (SSU rRNA). This genetically specified molecule is a key constituent of ribosomes, the "factories" that construct proteins in cells, and cells throughout time have needed it to survive. These features suggested to Woese in the late 1960s that variations in SSU rRNA (or more precisely in the genes encoding it) would reliably indicate the relatedness among any life-forms, from the plainest bacteria to the most complex animals. Small subunit ribosomal RNA could thus serve, in Woese's words, as a "universal molecular chronometer."

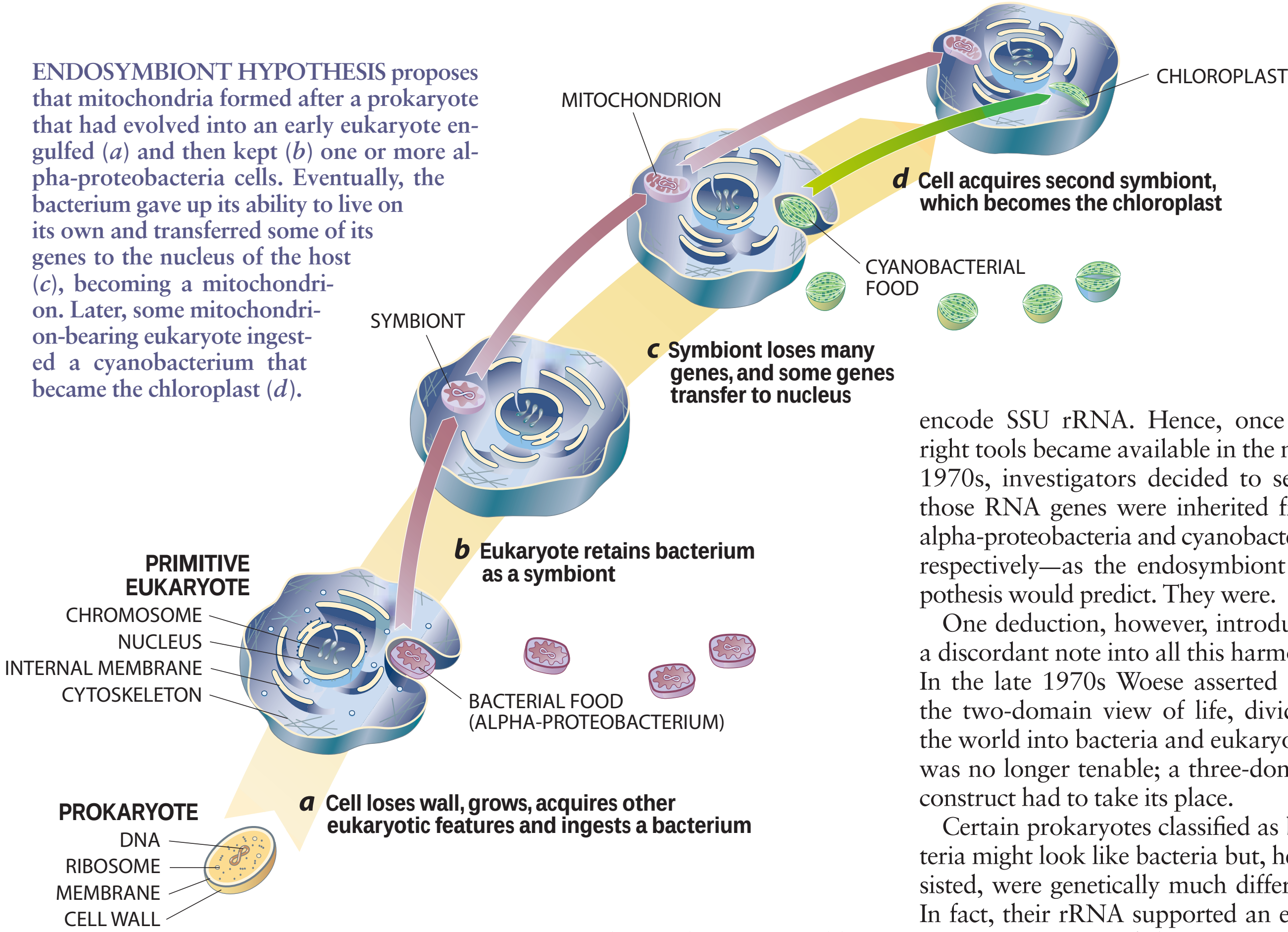
Initially the methods available for the project were indirect and laborious. By the late 1970s, though, Woese had enough data to draw some important inferences. Since then, phylogeneticists studying microbial evolution, as well as investigators concerned with higher sections of the universal tree, have based many of their branching patterns on sequence analyses of SSU rRNA genes. This accumulation of rRNA data helped greatly to foster consensus about the universal tree in the late 1980s. Today investigators have rRNA sequences for several thousands of species.

From the start, the rRNA results corroborated some already accepted ideas, but they also produced an astonishing surprise. By the 1960s microscopists had determined that the world of living things could be divided into two separate groups, eukaryotes and prokaryotes, depending on the structure of the cells that composed them. Eukaryotic organisms (animals, plants, fungi and many unicellular life-forms) were defined as those composed of cells that contained a true nucleus—a membrane-bound organelle housing the chromosomes. Eukaryotic cells



JANA BRENNING

ENDOSYMBIONT HYPOTHESIS proposes that mitochondria formed after a prokaryote that had evolved into an early eukaryote engulfed (*a*) and then kept (*b*) one or more alpha-proteobacteria cells. Eventually, the bacterium gave up its ability to live on its own and transferred some of its genes to the nucleus of the host (*c*), becoming a mitochondrion. Later, some mitochondrion-bearing eukaryote ingested a cyanobacterium that became the chloroplast (*d*).



CHRISTOPH BLUMRICH

also displayed other prominent features, among them a cytoskeleton, an intricate system of internal membranes and, usually, mitochondria (organelles that perform respiration, using oxygen to extract energy from nutrients). In the case of algae and higher plants, the cells also contained chloroplasts (photosynthetic organelles).

Prokaryotes, thought at the time to be synonymous with bacteria, were noted to consist of smaller and simpler nonnucleated cells. They are usually enclosed by both a membrane and a rigid outer wall.

Woese's early data supported the distinction between prokaryotes and eukaryotes, by establishing that the SSU rRNAs in typical bacteria were more similar in sequence to one another than to the rRNA of eukaryotes. The initial rRNA findings also lent credence to one of the most interesting notions in evolutionary cell biology: the endosymbiont hypothesis. This conception aims to explain how eukaryotic cells first came to possess mitochondria and chloroplasts [see "The Birth of Complex Cells," by Christian de Duve, Scientific American, April 1996].

On the way to becoming a eukaryote, the hypothesis proposes, some ancient anaerobic prokaryote (unable to use oxygen for energy) lost its cell wall. The more flexible membrane underneath then began to grow and fold in on itself. This change, in turn, led to formation of a nucleus and other internal membranes and also enabled the cell to engulf and digest neighboring prokaryotes, instead of gaining nourishment entirely by absorbing small molecules from its environment.

At some point, one of the descendants of this primitive eukaryote took up bacterial cells of the type known as alpha-proteobacteria, which are proficient at respiration. But instead of digesting this "food," the eukaryote settled into a mutually beneficial (symbiotic) relationship with it. The eukaryote sheltered the internalized cells, and the "endosymbionts" provided extra energy to the host through respiration. Finally, the endosymbionts lost the genes they formerly used for independent growth and transferred others to the host's nucleus—becoming mitochondria in the process. Likewise, chloroplasts derive from cyanobacteria that an early, mitochondria-bearing eukaryote took up and kept.

Mitochondria and chloroplasts in modern eukaryotes still retain a small number of genes, including those that encode SSU rRNA. Hence, once the right tools became available in the mid-1970s, investigators decided to see if those RNA genes were inherited from alpha-proteobacteria and cyanobacteria, respectively—as the endosymbiont hypothesis would predict. They were.

One deduction, however, introduced a discordant note into all this harmony. In the late 1970s Woese asserted that the two-domain view of life, dividing the world into bacteria and eukaryotes, was no longer tenable; a three-domain construct had to take its place.

Certain prokaryotes classified as bacteria might look like bacteria but, he insisted, were genetically much different. In fact, their rRNA supported an early separation. Many of these species had already been noted for displaying unusual behavior, such as favoring extreme environments, but no one had disputed their status as bacteria. Now Woese claimed that they formed a third primary group—the archaea—as different from bacteria as bacteria are from eukaryotes.

Acrimony, Then Consensus

At first, the claim met enormous resistance. Yet eventually most scientists became convinced, in part because the overall structures of certain molecules in archaeal species corroborated the three-group arrangement. For instance, the cell membranes of all archaea are made up of unique lipids (fatty substances) that are quite distinct—in their physical properties, chemical constituents and linkages—from the lipids of bacteria.

Similarly, the archaeal proteins responsible for several crucial cellular processes have a distinct structure from the proteins that perform the same tasks in bacteria. Gene transcription and translation are two of those processes. To make a protein, a cell first copies, or transcribes, the corresponding gene into a strand of messenger RNA. Then ribosomes translate the messenger RNA codes into a specific string of amino acids. Biochemists found that archaeal RNA polymerase, the enzyme that carries out gene transcription, more resembles its eukaryotic than its bacterial counterparts in complexity and in the nature of its interactions with DNA. The protein components of the ribosomes that translate archaeal messenger RNAs are also more like the ones in eukaryotes than those in bacteria.

Once scientists accepted the idea of three domains of life instead of two, they naturally wanted to know which of the two structurally primitive groups—bacteria or archaea—gave rise to the first eukaryotic cell. The studies that showed a kinship between the transcription and translation machinery in archaea and eukaryotes implied that eukaryotes diverged from the archaeans.

This deduction gained added credibility in 1989, when groups led by J. Peter Gogarten of the University of Connecticut and Takashi Miyata, then at Kyushu University in Japan, used sequence information from genes for other cellular components to "root" the universal tree. Comparisons of SSU rRNA can indicate which organisms are closely related to one another but, for technical reasons, cannot by themselves indicate which groups are oldest and therefore closest to the root of the tree. The DNA sequences encoding two essential cellular proteins agreed that the last common ancestor spawned both the bacteria and the archaea; then the eukaryotes branched from the archaea.

Since 1989 a host of discoveries have supported that depiction. In the past five years, sequences of the full genome (the total complement of genes) in half a dozen archaea and more than 15 bacteria have become available. Comparisons of such genomes confirm earlier suggestions that many genes involved in transcription and translation are much the same in eukaryotes and archaea and that these processes are performed very similarly in the two domains. Further, although archaea do not have nuclei, under certain experimental conditions their chromosomes resemble those of eukaryotes: the DNA appears to be associated with eukaryote-type proteins called histones, and the chromosomes can adopt a eukaryotic "beads-on-a-string" structure. These chromosomes are replicated by a suite of proteins, most of which are found in some form in eukaryotes but not in bacteria.

Nevertheless, Doubts

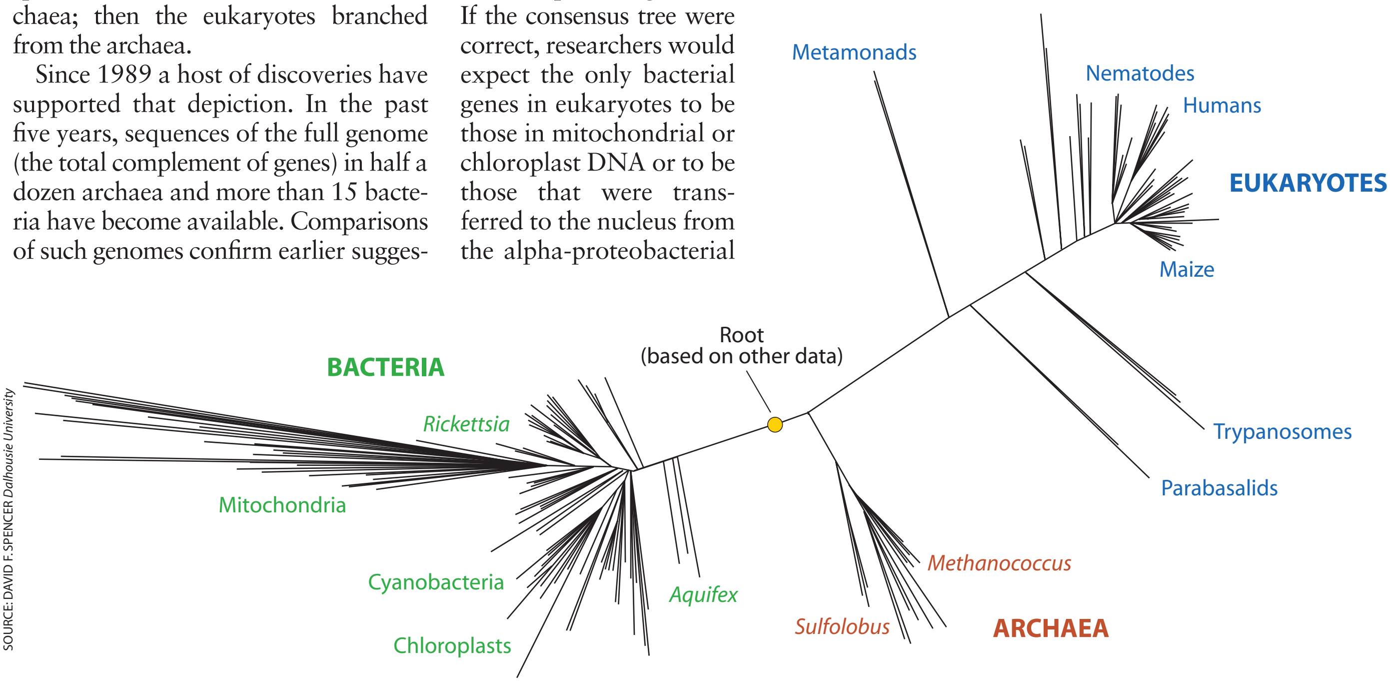
The accumulation of all these wonderfully consistent data was gratifying and gave rise to the now accepted arrangement of the universal genealogical tree. This phylogeny indicates that life diverged first into bacteria and archaea. Eukaryotes then evolved from an archaealike precursor. Subsequently, eukaryotes took up genes from bacteria twice, obtaining mitochondria from alpha-proteobacteria and chloroplasts from cyanobacteria.

Still, as DNA sequences of complete genomes have become increasingly available, my group and others have noted patterns that are disturbingly at odds with the prevailing beliefs. If the consensus tree were correct, researchers would expect the only bacterial genes in eukaryotes to be those in mitochondrial or chloroplast DNA or to be those that were transferred to the nucleus from the alpha-proteobacterial or cyanobacterial precursors of these organelles. The transferred genes, moreover, would be ones involved in respiration or photosynthesis, not in cellular processes that would already be handled by genes inherited from the ancestral archaean.

Those expectations have been violated. Nuclear genes in eukaryotes often derive from bacteria, not solely from archaea. A good number of those bacterial genes serve nonrespiratory and nonphotosynthetic processes that are arguably as critical to cell survival as are transcription and translation.

The classic tree also indicates that bacterial genes migrated only to a eukaryote, not to any archaea. Yet we are seeing signs that many archaea possess a substantial store of bacterial genes. One example among many is *Archaeoglobus fulgidus*. This organism meets all the criteria for an archaean (it has all the proper lipids in its cell membrane and the right transcriptional and translational machinery), but it uses a bacterial form of the enzyme HMGCoA reductase for synthesizing membrane lipids. It also has numerous bacterial genes that help it to gain energy and nutrients in one of its favorite habitats: undersea oil wells.

The most reasonable explanation for these various contrarian results is that the pattern of evolution is not as linear and treelike as Darwin imagined it. Al-



CHRISTOPH BLUMRICH; SOURCE: DAVID F. SPENCER *Dalhousie University*

RELATIONSHIPS among ribosomal RNAs (rRNAs) from almost 600 species are depicted. A single line represents the rRNA sequence in one species or a group; many of the lines reflect rRNAs encoded by nuclear genes, but others reflect rRNAs encoded by chloroplast or mitochondrial genes. The mitochondrial lines are relatively long because mitochondrial genes evolve rapidly. Trees derived from rRNA data are rootless; other data put the root at the colored dot, corresponding to the lowest part of the tree on pages 90 and 91.

though genes are passed vertically from generation to generation, this vertical inheritance is not the only important process that has affected the evolution of cells. Rampant operation of a different process—lateral, or horizontal, gene transfer—has also affected the course of that evolution profoundly. Such transfer involves the delivery of single genes, or whole suites of them, not from a parent cell to its offspring but across species barriers.

Lateral gene transfer would explain how eukaryotes that supposedly evolved from an archaeal cell obtained so many bacterial genes important to metabolism: the eukaryotes picked up the genes from bacteria and kept those that proved useful. It would likewise explain how various archaea came to possess genes usually found in bacteria.

Some molecular phylogenetic theorists—among them, Mitchell L. Sogin of the Marine Biological Laboratory in Woods Hole, Mass., and Russell F. Doolittle (my very distant relative) of the University of California at San Diego—have also invoked lateral gene transfer to explain a long-standing mystery. Many eukaryotic genes turn out to be unlike those of any known archaea or bacteria; they seem to have come from nowhere. Notable in this regard are the genes for the components of two defining eukaryotic features, the cytoskeleton and the system of internal membranes. Sogin and Doolittle suppose that some fourth domain of organisms, now extinct, slipped those surprising genes into the eukaryotic nuclear genome horizontally.

In truth, microbiologists have long known that bacteria exchange genes horizontally. Gene swapping is clearly how some disease-causing bacteria give the gift of antibiotic resistance to other species of infectious bacteria. But few researchers suspected that genes essential to the very survival of cells traded hands frequently or that lateral transfer exerted great influence on the early history of microbial life. Apparently, we were mistaken.

Can the Tree Survive?

What do the new findings say about the structure of the universal tree of life? One lesson is that the neat progression from archaea to eukaryote in the consensus tree is oversimplified or wrong. Plausibly, eukaryotes emerged not from an archaean but from some precursor cell that was the product of any number of horizontal gene transfers—events that left it part bacterial and part archaean and maybe part other things.

The weight of evidence still supports the likelihood that mitochondria in eukaryotes derived from alpha-proteobacterial cells and that chloroplasts came from ingested cyanobacteria, but it is no longer safe to assume that those were the only lateral gene transfers that occurred after the first eukaryotes arose. Only in later, multicellular eukaryotes do we know of definite restrictions on horizontal gene exchange, such as the advent of separated (and protected) germ cells.

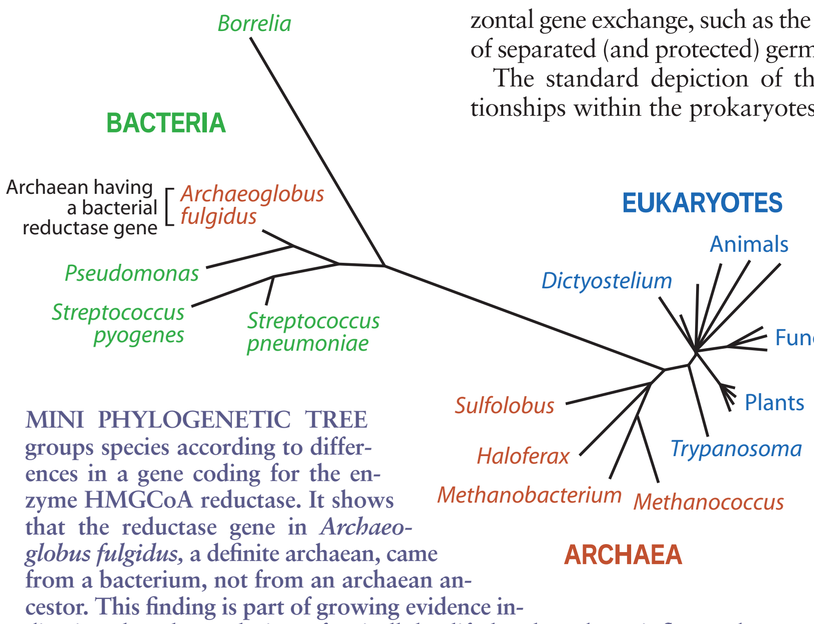
The standard depiction of the relationships within the prokaryotes seems too pat as well. A host of genes and biochemical features do unite the prokaryotes that biologists now call archaea and distinguish those organisms from the prokaryotes we call bacteria, but bacteria and archaea (as well as species within each group) have clearly engaged in extensive gene swapping.

Researchers might choose to define evolutionary relationships within the prokaryotes on the basis of genes that seem least likely to be transferred. Indeed, many investigators still assume that genes for SSU rRNA and the proteins involved in transcription and translation are unlikely to be moveable and that the phylogenetic tree based on them thus remains valid. But this nontransferability is largely an untested assumption, and in any case, we must now admit that any tree is at best a description of the evolutionary history of only part of an organism's genome. The consensus tree is an overly simplified depiction.

What would a truer model look like? At the top, treelike branching would continue to be apt [*see illustration on opposite page*] for multicellular animals, plants and fungi. And gene transfers involved in the formation of bacteria-derived mitochondria and chloroplasts in eukaryotes would still appear as fusions of major branches. Below these transfer points (and continuing up into the modern bacterial and archaeal domains), we would, however, see a great many additional branch fusions. Deep in the realm of the prokaryotes and perhaps at the base of the eukaryotic domain, designation of any trunk as the main one would be arbitrary.

Though complicated, even this revised picture would actually be misleadingly simple, a sort of shorthand cartoon, because the fusing of branches usually would not represent the joining of whole genomes, only the transfers of single or multiple genes. The full picture would have to display simultaneously the superimposed genealogical patterns of thousands of different families of genes (the rRNA genes form just one such family).

If there had never been any lateral transfer, all these individual gene trees would have the same topology (the same branching order), and the ancestral genes at the root of each tree would have all been present in the genome of the universal last common ancestor, a single ancient cell. But extensive transfer means that neither is the case: gene trees will differ (although many will have regions of similar topology), *and*



MINI PHYLOGENETIC TREE groups species according to differences in a gene coding for the enzyme HMGCoA reductase. It shows that the reductase gene in *Archaeoglobus fulgidus,* a definite archaean, came from a bacterium, not from an archaean ancestor. This finding is part of growing evidence indicating that the evolution of unicellular life has long been influenced profoundly by lateral gene transfer (occurring between contemporaries). The consensus universal tree does not take that influence into account.

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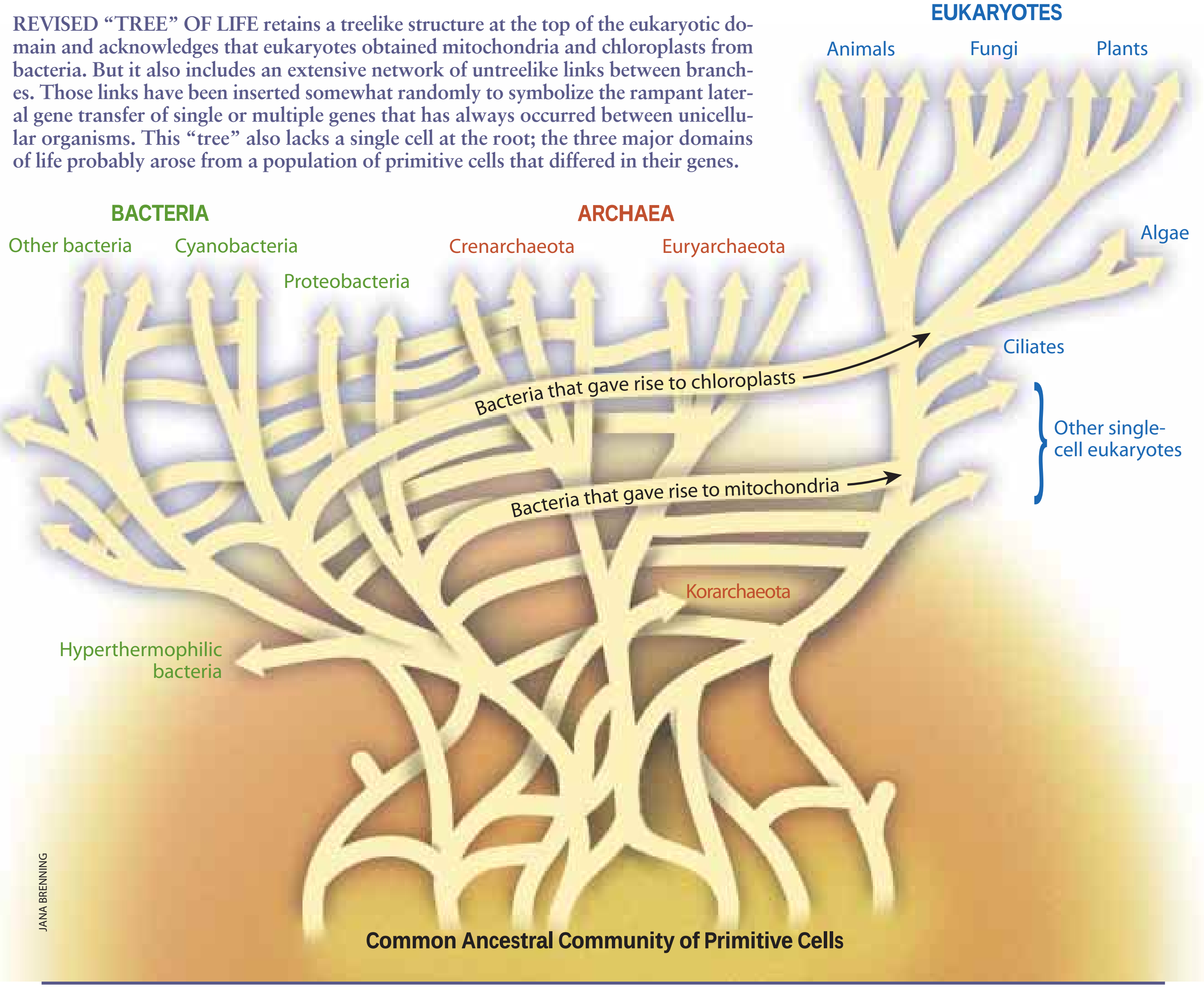
there would never have been a single cell that could be called the last universal common ancestor.

As Woese has written, "The ancestor cannot have been a particular organism, a single organismal lineage. It was communal, a loosely knit, diverse conglomeration of primitive cells that evolved as a unit, and it eventually developed to a stage where it broke into several distinct communities, which in their turn become the three primary lines of descent [bacteria, archaea and eukaryotes]." In other words, early cells, each having relatively few genes, differed in many ways. By swapping genes freely, they shared various of their talents with their contemporaries. Eventually this collection of eclectic and changeable cells coalesced into the three basic domains known today. These domains remain recognizable because much (though by no means all) of the gene transfer that occurs these days goes on within domains.

Some biologists find these notions confusing and discouraging. It is as if we have failed at the task that Darwin set for us: delineating the unique structure of the tree of life. But in fact, our science is working just as it should. An attractive hypothesis or model (the single tree) suggested experiments, in this case the collection of gene sequences and their analysis with the methods of molecular phylogeny. The data show the model to be too simple. Now new hypotheses, having final forms we cannot yet guess, are called for. SA

REVISED "TREE" OF LIFE retains a treelike structure at the top of the eukaryotic domain and acknowledges that eukaryotes obtained mitochondria and chloroplasts from bacteria. But it also includes an extensive network of untreelike links between branches. Those links have been inserted somewhat randomly to symbolize the rampant lateral gene transfer of single or multiple genes that has always occurred between unicellular organisms. This "tree" also lacks a single cell at the root; the three major domains of life probably arose from a population of primitive cells that differed in their genes.



The Author

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Further Information

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by Shawn Carlson

Gamma-Ray Bursts Come Home

Sometimes it's better to be lucky than good. On January 23, 1999, a satellite-based instrument called the Burst and Transient Source Experiment (BATSE) detected a bright flash of gamma rays coming from the constellation Boötes. For years, astronomers had caught sight of such gamma-ray bursts several times a week in every part of the sky [see "Gamma-Ray Bursts," by Gerald J. Fishman and Dieter H. Hartmann; Scientific American, July 1997]. But precious little was known about these sources of incredible energy—how do they form and from where do they originate?—because they are so fleeting. They rarely shine longer than a few minutes (some exist for only a tiny fraction of a second), providing little time for astronomers to bring a variety of instruments to bear. Indeed, even though that night's event was quite bright and lasted almost two minutes, BATSE could only localize the source to a disk on the sky about four full moons wide.

Enter Lady Luck. At the moment the burst went off, another satellite called Beppo-SAX just happened to be imaging the same section of sky, using a wide-field camera for x-rays (radiation of somewhat lower frequency than gamma rays). Within six hours of receiving a detection alert from BATSE via e-mail, scientists had fixed the precise position of a bright x-ray source that was within the BATSE-identified region but that had not been there before.

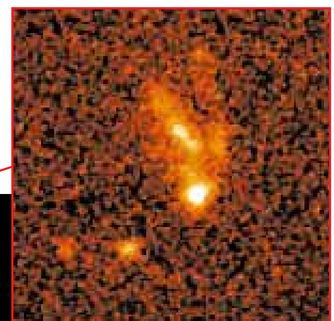
Astronomers were also able to obtain optical images of the gamma-ray burst. Just 20 seconds after the first alert had sounded, a robotic optical telescope in Los Alamos, N.M., had zeroed in with four wide-field cameras. After other researchers had identified the burst's precise position, the Los Alamos group discovered that its early images had captured a bright (9th magnitude) but rapidly fading star at that exact location.

The next night the mighty Keck II, the 10-meter monster telescope that sits atop the Mauna Kea volcano in Hawaii, swung into action. With its huge light-gathering surface, it measured the object's redshift and determined that the gamma-ray burst had originated halfway across the universe.

That's when champagne corks started popping. For something so distant to shine so intensely in our sky, it must be incredibly bright at its source. In fact, whatever produced the gamma rays had, for a while at least, been the brightest object ever identified. Without a doubt, astronomers had made a major discovery. And now they aim to get amateurs in on the fun.

Why amateurs? Because the BATSE team members know that had the Beppo-SAX satellite been looking elsewhere that night, astronomers never would have been able to direct ground-based telescopes to measure the object's magnitude and distance. And even then it took precious hours to fix a position of the rapidly changing object.

A better system would consist of numerous observers looking inside the BATSE-identified region within minutes of the event's detection. With enough



THE SKY is filled with mysterious events, such as this gamma-ray burst (inset) *detected on January 23, 1999. A network of amateur astronomers could help reveal the secrets of such incredibly powerful—but maddeningly brief—blasts of energy.*

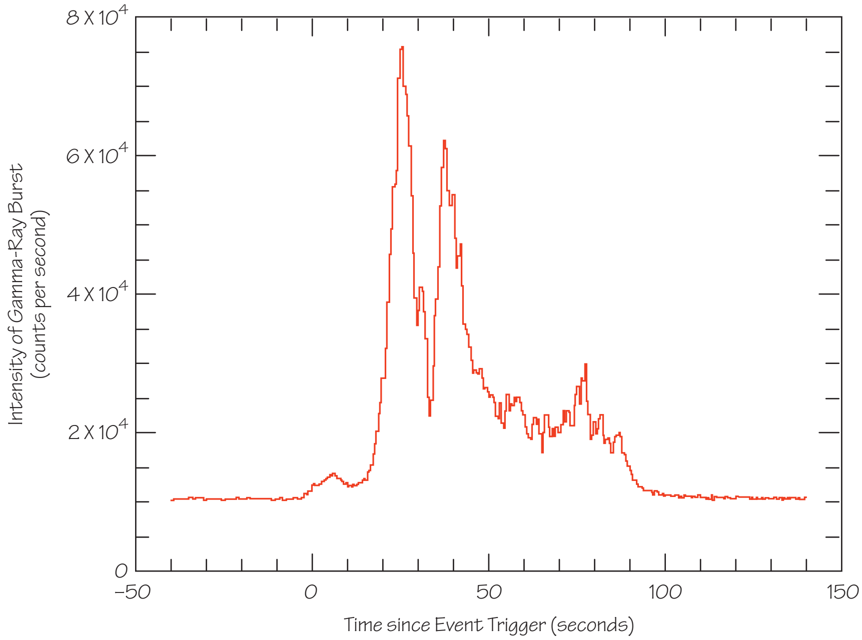
JOHNNY JOHNSON; HUBBLE SPACE TELESCOPE/ SPACE TELESCOPE SCIENCE INSTITUTE (*inset*) people, chances are that someone would quickly find the new object and report in so that other observations could be set in motion. Thus, the BATSE team has wanted to create an international network of both professionals and amateurs who will be on standby to help when BATSE detects a gamma-ray burst.

Amateur involvement is not as far-fetched as it may sound. Thousands of hobbyists own research-quality telescopes. But even instruments with mirrors as small as 25 centimeters could participate. (Such devices could either be bought for about $700 or fashioned, albeit with considerable time and effort, for less than $100.) And these days many amateur telescopes are equipped with sensitive charge-coupled-device (CCD) cameras that can capture an electronic image of a star field. A personal computer could then process this information in real time to identify new objects. Some of the more expensive telescopes are even automated: they can receive instructions via the Internet and take images anywhere in the sky—without an observer even having to be there. Clearly, the amateur community is ready to be a vital partner in uncovering the secrets of these strange sources of gamma-ray energy.

The network is being developed and overseen by the American Association of Variable Star Observers, located in Cambridge, Mass. Founded in 1911, the AAVSO is the oldest institution in the U.S. dedicated to helping amateurs make astronomical measurements of scientific importance.

The AAVSO organizes and compiles data on thousands of variable stars. To date, it has logged more than nine million measurements of star brightness. Janet Mattei, the executive director and a dear friend of mine, is a person with boundless energy, political savvy and a passion for advancing amateur astronomy. If anyone can keep this network going, it's Janet. And the observing team is being led by Gerald J. Fishman, the principal investigator on the BATSE project, and Mario Motta, a cardiologist and avid amateur astronomer from Lynnfield, Mass.

To join the team, log on to the AAVSO's Web site (www.aavso.org) and fill out the on-line application, including information about your telescope's size, field of view, and location. In addition,



JOHNNY JOHNSON; SOURCE: NASA

***INTENSE BUT EPHEMERAL** energy is a characteristic of gamma-ray bursts, making it difficult to pinpoint their exact locations. The event that was detected on January 23, 1999, lasted less than two minutes.*

just before embarking on a long night of astronomical adventure, you need to notify the AAVSO by sending an e-mail to aavso@aavso.org. Then, whenever BATSE detects a gamma-ray burst and obtains data on the center and width of the target region, a computer at the AAVSO will automatically send this information via e-mail to everyone who has logged on for that night.

But what about people who don't happen to be observing when an event is detected but who could fire up their backyard telescopes on a moment's notice? The AAVSO intends to reach them by pager, with the coordinates of the gamma-ray burst contained in a text message. So even sleeping astronomers can be alerted to the opportunity to make scientific history.

Of course, BATSE's determination of the location of an event will always suffer a large uncertainty. But if even 10 observers are on-line and scrutinize the identified area with wide-field imaging CCDs, it seems likely that many of the optical companions of a gamma-ray burst will be captured within minutes of receiving the alert. Participants can then e-mail their results to the AAVSO so that everyone on the network can see the information in real time.

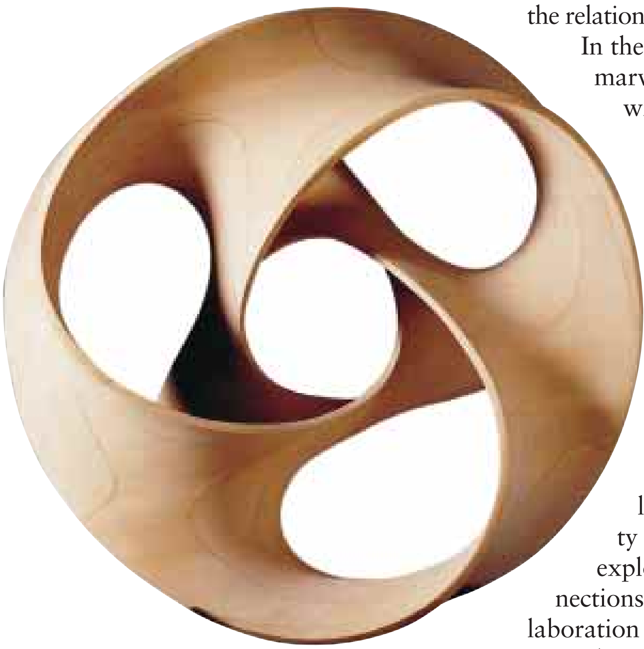
Obviously, there's a better way to do all this. The ideal system would use the information in the AAVSO database to assign a particular spot within the BATSE-identified region to each on-line observer, thus maximizing coverage of the section of the sky that contains the gamma-ray burst and thereby increasing the likelihood that someone will find it. Also, the simplest way to locate the optical companions of a gamma-ray burst on a CCD image is to run a program that identifies all the stars on the image and then compares them against stars in an electronic catalogue, like the one NASA compiled to provide guide stars for the Hubble Space Telescope.

But it will take a top-notch programmer to write the computer code that can do all this. Unfortunately, being a nonprofit organization, the AAVSO doesn't have the budget to hire such a person. So if you're a computer expert and would like to volunteer your talents to make a major contribution to science, please contact Janet Mattei at 617-354-0484. It's a fantastic opportunity for you to make a lasting contribution to unraveling one of the greatest mysteries in astronomy. SA

For more information about this and other projects, visit the Society for Amateur Scientists's Web site at earth.thesphere.com/sas/WebX.cgi. You may also write the society at 4735 Clairemont Square PMB 179, San Diego, CA 92117, or call them at 619-239-8807.

by Ian Stewart

Real and Virtual Sculptures



Mathematicians are convinced that their subject is beautiful, a belief many people find dubious. Grade school battles with arithmetic or algebra can be characterized in many ways, but "beautiful" does not readily spring to mind for most math students. Nevertheless, mathematics possesses beauty on many levels. The average person may find it hard to appreciate the logical elegance of a satisfying mathematical proof. But the beauty of geometric forms is very close to the aesthetics of the visual arts—especially sculpture—and is much more accessible to the nonmathematician.

I have discussed mathematically inspired sculptures before ("The Sculptures of Alan St. George," May 1996). The correspondence generated by that column revealed the existence of an astonishing variety of mathematical art; I could easily devote a year's worth of columns to the topic. In this column, I'm going to examine the connections between the mathematics of minimal surfaces and the exquisite wood-laminate sculptures made by artist Brent Collins of Gower, Mo. As you will see, the tale also poses some critical questions about the relation between real and virtual art.

In the 1980s Collins was creating marvelous abstract sculptures without any conscious intention of giving them mathematical significance. Over time, though, he became aware that he was intuitively tending to minimize the surface area between the edges of his sculptures. In effect, he was reproducing some basic topological forms. In 1995 Collins joined forces with computer scientist Carlo H. Séquin of the University of California at Berkeley to explore the mathematical connections of his artworks. Their collaboration is described in detail in the journal *Leonardo* (Vol. 30, No. 2, 1997, pages 85–96).

The key form here is the saddle, a smooth warped surface shaped like the thing you sit on when you ride a horse. Saddles are the basic components of minimal surfaces. To a mathematician, a minimal surface is one that has the smallest possible area while still complying with a given restraint that prevents the area from shrinking to zero (for example, the surface must span a given curve).

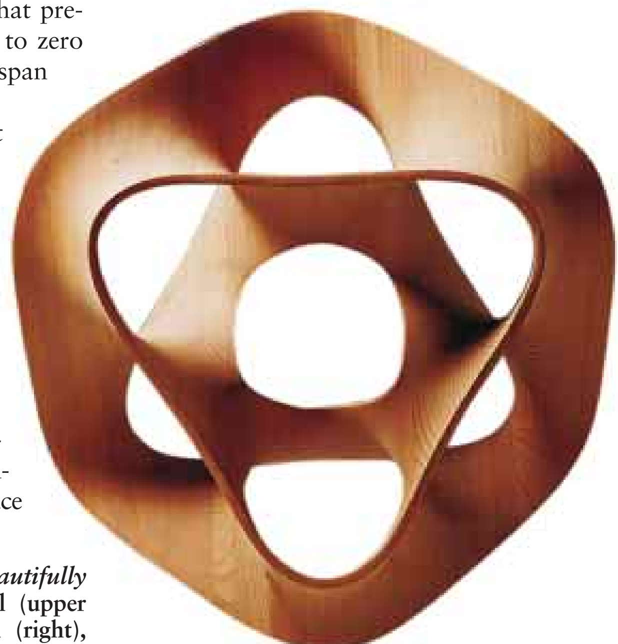
For a physical analogue, twist a wire into the shape of a curve, dip it into soapy water and observe the shape of the resulting soap film. Even if the wire makes complicated three-dimensional loops and knots, the film of soap always looks elegant and well proportioned. Moreover, it is everywhere saddle-shaped. This property is a consequence of area minimization, which forces the surface to have zero curvature. That doesn't mean that the surface is flat: it means that around every point the surface is like a saddle, curving up in one direction and down in another.

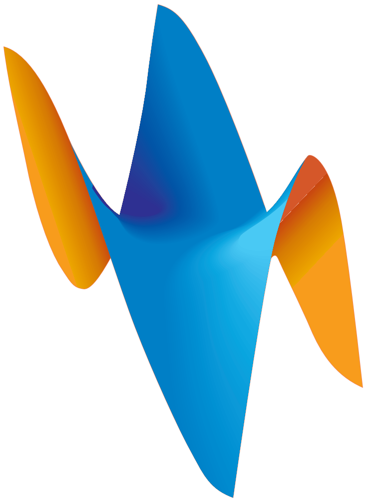
MINIMAL SURFACES are beautifully rendered in **Hyperbolic Trefoil** *(upper left) and* **Hyperbolic Hexagon** *(right), both created by sculptor Brent Collins.*

Collins began with surfaces formed from saddles but quickly progressed to more complex forms involving what mathematicians call a "monkey saddle." As its name suggests, this surface resembles a whimsical saddle on which a monkey could sit—it has three directions of downward curvature, two to make room for the monkey's legs and a third for its tail [*see illustration on left side of page 100*]. In between them are three directions of upward curvature. A closed loop around the edge of such a saddle curves up and down three times, forming six "ripples." A similar loop around the base of a standard saddle forms four ripples. There are also "quadruped" and higher-order saddles.

To see how Collins incorporated these shapes into his artworks, consider *Hyperbolic Hexagon,* which Collins completed in 1995. It comprises six standard saddles linked in a ring formation [*see photograph below*]. The sculpture is closely related to a minimal surface known as a Scherk tower, which consists of a series of linked saddles that create holes that lead in alternating di-

PHILLIP GELLER





MONKEY SADDLE is a minimal surface with three directions of downward curvature.

rections [*see illustration at upper right*]. If you take a six-story Scherk tower and bend it into a circle, so that the top and bottom of the tower join together, you get a toroidal ring in the general shape of *Hyperbolic Hexagon.*

The discussions between Collins and Séquin led to the conception of a dramatic new structure, in which the Scherk tower is given a 90-degree twist before its ends are joined—rather like the construction of a Möbius band, in which a paper strip is twisted 180 degrees before its ends are connected. The twist makes the two sides of the paper strip merge into each other, so that if you start painting one side red and keep going, eventually you are forced to paint the "other" side red as well. That is, the Möbius band is a one-sided surface. An untwisted Scherk tower is like an ordinary strip of paper: it has two distinct sides, which can be painted in two different colors. The same is true of *Hyperbolic Hexagon.* But an analogous surface made from a twisted Scherk tower would be like a Möbius band and have only one side.

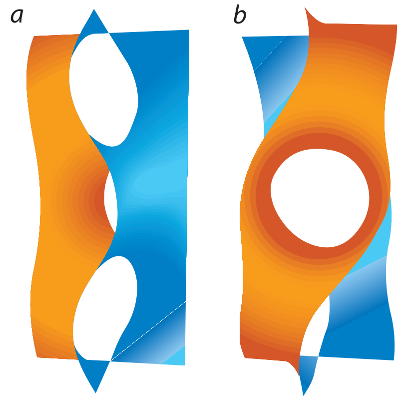
The edges at the top and bottom of a Scherk tower form plus-sign crosses and therefore fit perfectly if the twist is a multiple of 90 degrees. The twist must also take account of the tower's holes, however. Because the holes in a Scherk tower alternate directions, twists through an odd multiple of 90 degrees work only for towers with an odd number of stories, and twists through an even multiple of 90 degrees work only for towers with an even number of stories. Collins's 1996 sculpture *Hyperbolic Trefoil,* shown at the top of page 98, is a toroidal ring formed by giving a three-story Scherk tower a 270-degree twist and then joining its ends.

Séquin has named these shapes "Scherk-Collins surfaces." By formulating Collins's ideas in mathematical terms, it became possible to devise new variations in a systematic manner. The mathematical approach has also simplified the manufacturing of the artworks. Collins's sculptures are made from laminated wood in a delicate and time-consuming process, so before starting on a final version he makes prototypes from PVC piping and beeswax sheets. This approach provides an accurate model of the surface, but it takes several days. To speed up the process, Séquin—with the aid of Houman Meshkin, one of his undergraduate students—developed a graphics program that can display Scherk-Collins surfaces on a computer screen.

The program provides a choice of certain geometric parameters, giving the artist considerable freedom to stretch or otherwise deform the surface in search of an aesthetically pleasing result. The more obvious parameters are the number of stories in the tower and the amount of twist, but others control, for instance, the size of the holes. The tower itself is also generalized, allowing the introduction of variants such as a tower that links monkey saddles rather than standard ones. Once the surface has been molded on screen, prototyping tools can transform the virtual sculpture into a real object. Séquin has already created dozens of models of Scherk-Collins surfaces using this method.

There is, however, a more controversial alternative. Computer graphics have become so powerful that the virtual sculpture can be made to look almost exactly like the real thing. For example, graphics software can give the image almost any desired surface texture, so that it can look like grained wood or shiny copper or lizard skin or cloth. Printouts of the virtual sculpture would be pretty much indistinguishable from photographs of a real sculpture. And an art lover equipped with a virtual-reality headset could "walk around" the virtual sculpture to get a vivid three-dimensional impression.

Given all this, is it really necessary to *build* the sculpture at all? Might it not just remain virtual? Most traditional artists would probably say no, but the opinions of future generations—who will presumably be well acquainted with virtual-reality systems—could differ. Collins is unequivocal: "As a species evolved for toolmaking and use, human beings have aesthetic empathy for handmade art objects and will always need them as revelations of our nature." In other words, you can't beat the real thing. SA



SCHERK TOWERS are linked saddles that form a series of holes. A three-story tower (a) *can be twisted 90 degrees* (b). *Joining its ends will then create a one-sided surface.*

ILLUSTRATIONS BY BRYAN CHRISTIE

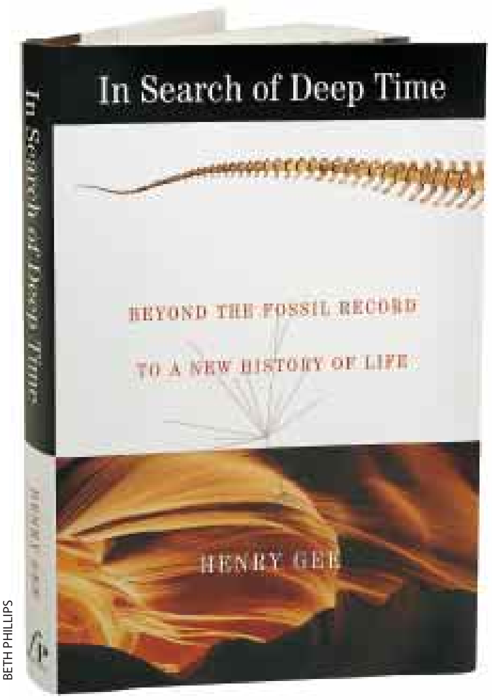
FEEDBACK

In "Cone with a Twist" [October 1999], I described the sphericon, a curious solid made by slicing a double-cone in half and then twisting one of the halves. As I suspected, some readers recognized the shape. David Bean of Arlington, Mass., wrote, "I ran across one about four years ago, molded of Super Ball plastic, that I guessed had been abandoned by a dog in a park. . . . Mine is about the weight of a lacrosse ball and rolls very nicely. But the quality that must endear it to dogs is its totally confounding bouncing. It's far worse than a football!" Bob Whitefield of Chapel Hill, N.C., shed further light on the doggy mystery: "The sphericon . . . is the exact same shape as 'The Wobbler,' one of my dog's favorite rubber toys. According to the manufacturer, Classic Products, the Wobbler is patented." In a more serious vein, several readers noted that the sphericon is a special case of an oloid, a shape invented by the late Swiss artist Paul Schatz. —*I.S.*

WHAT THE MEDIA DON'T TELL YOU ABOUT EVOLUTION

Review by Kevin Padian

In Search of Deep Time: Beyond the Fossil Record to a New History of Life
BY HENRY GEE
Free Press, New York, 1999 ($26)



BETH PHILLIPS

This is a subversive book. Read it only if you want to know how scientists actually do their work, as opposed to the mythology of textbooks and documentaries. In it, you will discover how and why the beloved Linnean system of taxonomy—the one that gave us classes and orders and families, oh my!—is being replaced by a wholly evolutionary way of looking at nature. Be warned: you won't learn this on TV. But you will be able to understand what scientists are talking about when, for example, they claim that birds *are* dinosaurs.

Henry Gee (pronounced like the letter) is an editor and senior writer at *Nature*, one of the two weekly journals that every scientist pores over faithfully. His training is as a paleontologist, but he got his education during one of those interesting times in the history of a discipline when a paradigm shift is occurring. As it happened, he got caught in the middle of it, so he writes with the viewpoint of someone who sees both sides. The discipline that shifted was not so much paleontology but systematics, or the reasoning behind classification. Classifications changed in all branches of biology, but the revolution began in vertebrate paleontology.

Here's what happened. In the 1950s a German entomologist named Willi Hennig put forth a system of classifying organisms in which only evolutionary innovations could be used to reconstruct relationships. Hennig's reasoning, which was also Charles Darwin's, was that classification should be based strictly on ancestry, and because these innovations were the closest tracers of most recent common ancestry, they should be used to the exclusion of all other features.

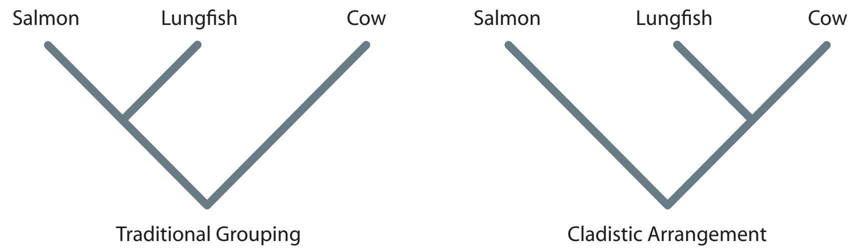
Before this time, from Linnaeus in the 1750s to the present, general similarities (not strictly innovative ones) were also used, because general similarities among organisms (as long as they connoted a common genetic basis) tended to hold groups together as ecological as well as evolutionary units. Thus, for example, although biologists had long realized that birds evolved from some kind of reptile, they did not subsume birds as a group *within* reptiles. Rather, because birds were so different from reptiles, the terms "bird" and "reptile" denoted two separate and equal classes of vertebrates. A more consistent approach, true to evolutionary history, is always to rank descendant groups as parts of their ancestral units (humans are unique, but they are also members of the larger ape, primate and mammal groups). The systematists can then avoid constructing taxonomic groups that have no natural counterpart (such as the conventional meaning of "reptiles" without birds).

The classic example, recounted by Gee, is in classifying the salmon, the lungfish and the cow. Traditionally, the salmon and lungfish are grouped as fishes, and the cow is a mammal [*see illustration on opposite page*]. But Hennig's system recognizes that the features we use to group the salmon and lungfish are only general fishlike things related to living in water that applied to the original vertebrates. So the salmon and lungfish are not related by any evolutionary innovations. Instead the lungfish and the cow share some heretofore unique features that the salmon lacks, such as the presence of nasal passages that open into the throat and the bony configuration of the limbs, so they are grouped together as choanates. To many, the latter arrangement seems pointless, but if the point of classification is to uncover the history of life and to group it accordingly, this arrangement succeeds better than traditional methods.

A Radical Upbringing

As a Ph.D. student in the mid-1980s, Gee found himself thrown in with the most radical group of Hennigians in paleontology: the fossil fish section of London's Natural History Museum. Cladistics, as Hennig's system came to be called (after the Greek word for "branch"), was mother's milk to him, and he tells many amusing tales of heresy and hogwash in the pubs, bars, correspondence columns and scientific conferences where cladistics was argued, championed and disparaged. Those were heady days indeed. But if this book simply recounted the paradigm shift in systematic philosophy, it would be of limited interest. Instead it describes the development of a whole new way of thinking about biology and particularly about what we know of the history of life, what we can and can't know and study scientifically, and how this knowledge affects even the way we narrate our stories about the evolution of life.

In Search of Deep Time would be a



FROM IN SEARCH OF DEEP TIME

good title for a book about the history of geochronology, which this is not. An earlier working title was *Thirty Ghosts,* an allusion to a quotation from Arthur C. Clarke and Stanley Kubrick's *2001: A Space Odyssey* to the effect that behind every human being now living stand thirty ghosts. The number is of course much greater, but the point is that our lineal chain of ancestry is both unimaginably extensive and largely unknowable. Gee describes the difficulty of reconstructing the past using his experience searching for hominid fossils in Africa with Meave Leakey's crew. A bone you pick up might be a hominid and might persuasively be not far from the direct line to living humans. But you can never really know, because not enough information is preserved. Deep Time, with its attendant destruction of information from the geologic past, has wiped away direct evidence. We have to reconstruct evolutionary history, as we reconstruct human history, from the bits and pieces we have available to us.

But there is more: we have to have a *method* in order to do testable science. Gee shows that many traditional explanations of major evolutionary transitions are not testable and therefore have no scientific content. For example, let's say that you don't agree with the overwhelming evidence that birds evolved from small carnivorous dinosaurs (see my article with Luis M. Chiappe in *Scientific American,* February 1998), because as far as you're concerned, flight had to evolve in the trees, and dinosaurs couldn't climb trees. This statement may be true or false, but it's not scientific, because you're making a statement about the *process* of evolution (how flight had to evolve) that you're not allowing to be tested by any contradictory *patterns* of evolution.

Testing Evolutionary Scenarios

In the case of how flight evolved, the patterns of evolution tell a different story, and here is where cladistics comes in. Every cladistic analysis of the relationships of birds to other animals, involving dozens of fossil animals and hundreds of characteristics, has placed birds squarely within small carnivorous dinosaurs. Gee's point is that maybe bird ancestors could climb trees and maybe they couldn't, but we'll never know for sure. The origin of birds is a question of pattern that can be tested by the distribution of innovative features that indicate closest evolutionary relationships; ideas about how flight must have evolved, he says, rely on faith in the particular workings of natural selection or other evolutionary processes. So which kind of knowledge is a more reliable guide to the ancestry of birds? Or, as Chico Marx once said in a movie in which he is discovered in a compromising position with another man's wife, "Who are you going to believe—me, or your own eyes?"

Does this mean that we can't know about anything but genealogy in extinct organisms? Not so, I think, and here I would be a little less hard-nosed than Gee's orthodox cladists. A good phylogeny can test hypotheses about evolutionary processes and particular historical pathways. If phylogenies show that humans evolved from semiarboreal limb-swingers rather than from quadrupedal sprinters, that would help explain why we have hands rather than hooves and why we can pitch baseballs better than most cows can. Gee shows, however, that in explaining evolutionary history we have to be careful not to see our thirty ghosts as trying to become "like us." It is often assumed that the "small" brains of earlier hominids were inferior to ours, but these creatures saw their world in different terms than we do ours, and after all, their world *was* different. Nevertheless, their brains were clearly adequate to the task, not striving to become what textbook authors, apparently without irony, call "fully human."

A working title was Thirty Ghosts, *an allusion to* 2001: A Space Odyssey *to the effect that behind every human being now living stand thirty ghosts.*

Divorcing evolutionary pattern from process in this way, we see that the origin of tetrapods and their emergence onto land, the origin of birds and the evolution of flight, and the origin of humans and the inception of speech are pairs of evolutionarily coupled but logically separate problems. If we assume that the second member of each pair was the reason for the first, we will never learn anything new about evolutionary history.

This is an important book because it clearly explains the workings and applications of the most versatile new implement in the toolbox of evolutionary biology. Twenty years after the hegemony of cladistics was established, the public remains almost completely ignorant of Hennig's method and how it is applied to problems in the history of life.

Gee explains it all congenially and clearly, with wit, originality and self-deprecating humor. It is like having an affable, bemused, literate and somewhat peripatetic cousin take you around his workplace; only in this case, the workplace is a zoo full of extinct animals, the keepers at first seem like weirdos with some kind of secret knowledge that they're trying to impart to you, and the signs on the cages make you blink and look twice at the animals. Oprah may not select this one for her book club, but I'll tell you what: if you've been reading newspaper and science magazine accounts of contentious issues in paleontology and evolutionary biology and wondering what's *really* behind so much of the debate, this is the book for you.

KEVIN PADIAN is professor of integrative biology and curator in the Museum of Paleontology at the University of California, Berkeley. He is the editor, with Philip J. Currie, of Encyclopedia of Dinosaurs *(Academic Press, 1997).*

THE EDITORS RECOMMEND

RARE EARTH: WHY COMPLEX LIFE IS UNCOMMON IN THE UNIVERSE. Peter D. Ward and Donald Brownlee. Copernicus, an imprint of Springer-Verlag New York, 2000 ($27.50).

Unlike many scientists who think that intelligent life may be abundant in the universe, Ward and Brownlee contend that any life found on other planets is most likely to be primitive—microbes or their equivalents. They advance what they call the Rare Earth Hypothesis, holding that Earth is probably rare among planets in orbiting a star that has had a fairly constant output of energy for billions of years and in being "of suitable size, chemical composition, and distance from the sun to enable life to thrive." Primitive organisms thrive on Earth in such harsh environments as hydrothermal vents, the authors note, and harsh conditions are likely to be the norm on other planets able to support any kind of life. Ward and Brownlee are at the University of Washington, where Ward is professor of geological sciences and zoology and Brownlee is professor of astronomy. Although simple life is probably abundant in the universe, they say, "*complex* life—animals and higher plants—is likely to be far more rare than is commonly assumed."

INSECT LIVES: STORIES OF MYSTERY AND ROMANCE FROM A HIDDEN WORLD. Edited by Erich Hoyt and Ted Schultz. John Wiley & Sons, New York, 1999 ($27.95).

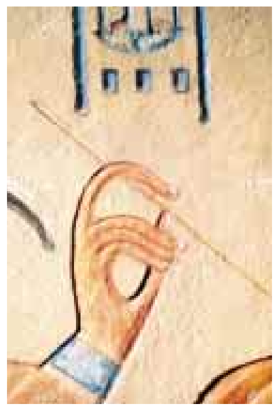
"Alien creatures have overrun planet Earth. They wear their skeletons on the outside, bite sideways, smell with antennae, taste with their feet, and breathe through holes in the sides of their bodies. . . . They are the insects." From the human viewpoint, "insects are aliens, denizens of another world, shadow opposites with whom we share planet Earth."

FROM *INSECT LIVES*

Starting from that perspective, Hoyt (a Scottish science writer) and Schultz (an entomologist at the Smithsonian Institution) had an inspiration: put together a book of writings on these intriguing and ubiquitous aliens, with an emphasis on good writing. The result is mighty good reading, abetted by many rewarding illustrations. The 76 entries include not only essays by scientists, as one would expect, but also poems by the likes of Burns and Wordsworth, passages from the Bible and even excerpts from the 1954 screenplay for *Them!,* one of the first insect movie thrillers. Taken altogether, the collection delivers what Hoyt and Schultz promise in their introduction—"a sweeping tour of the human fascination with insects."

THE STORY OF WRITING. Andrew Robinson. Thames & Hudson, New York, 1999 ($19.95).

"Writing is among the greatest inventions in human history, perhaps *the* greatest invention, since it made history possible." Thus Robinson, literary editor of the (London) *Times Higher Education Supplement,* introduces his scholarly and fascinating study of alphabets, hieroglyphics and pictograms. He says he is not presenting the full history of writing, focusing instead on "an account of the scripts used in the major civilizations of the ancient world, of the major scripts we use today, and of the underlying principles that unite the two." But a great deal of the history is here, together with more than 350 splendidly helpful (and viewable) illustrations: cuneiform, Egyptian hieroglyphs, Mayan glyphs, Chinese and Japanese writing, and scripts based on alphabets.



FROM *THE STORY OF WRITING*

Robinson is also interested in the current movement toward increased communication through logograms, or pictographic symbols. Could they be expanded into a universal writing system that would transcend language differences? Robinson thinks not, asserting that whereas logograms can be helpful, "full writing is based on speech." The book is a paperback edition of a hardback published in 1995.

WEAVING THE WEB: THE ORIGINAL DESIGN AND ULTIMATE DESTINY OF THE WORLD WIDE WEB BY ITS INVENTOR. Tim Berners-Lee, with Mark Fischetti. HarperSanFrancisco, 1999 ($26).

Sometimes it seems that, as Athena is said to have sprung fully armed from the brow of Zeus, the Web sprang fully matured from some electronic brow. Not so. It originated from a concept in Berners-Lee's mind and matured slowly. There was, he says, no "Eureka!" moment. Instead: "*Suppose all the information stored on computers everywhere were linked,* I thought [in 1980]. *Suppose I could program my computer to create a space in which anything could be linked to anything.*" The structure he envisioned would overcome the incompatibility among computers that made them unable to communicate with one another.

Berners-Lee is still shepherding that vision as director of the World Wide Web Consortium while he occupies the 3Com Founders chair at the Massachusetts Institute of Technology Laboratory for Computer Science. He describes the evolution of the Web and considers the problems that have arisen as it has matured, including privacy, encryption, filtering and trust among users. As for the future of the Web, he has a two-part dream. In the first part, "the Web becomes a much more powerful means for collaboration between people." In the second, the collaborations extend to include computers. "Machines become capable of analyzing all the data on the Web—the content, links, and transactions between people and computers."

FLU: THE STORY OF THE GREAT INFLUENZA PANDEMIC OF 1918 AND THE SEARCH FOR THE VIRUS THAT CAUSED IT. Gina Kolata. Farrar, Straus and Giroux, New York, 1999 ($25).

"The 1918 flu epidemic puts every other epidemic of this century to shame," Kolata writes. "It was a plague so deadly that if a similar virus were to strike today, it would kill more people in a single year than heart disease, cancers, strokes, chronic pulmonary disease, AIDS, and Alzheimer's disease combined." It is also "one of history's great conundrums," she says, in that despite its profound impact, little is said or known about it today. But a determined band of researchers has searched for and found the deadly virus in tissues preserved from victims. It is their story that Kolata (a science writer for the *New York Times*) tells, skillfully weaving into it an account of the epidemic's devastating effects and the pathology of the disease. Although the search for the causative virus has succeeded, she says, the effort to understand why the 1918 flu was such a killer has not. "We definitely have the right suspect," molecular pathologist Jeffery Taubenberger told Kolata, "but we do not yet know how the murder was committed." SA

WONDERS

by Philip and Phylis Morrison

Time Travelers in the Field

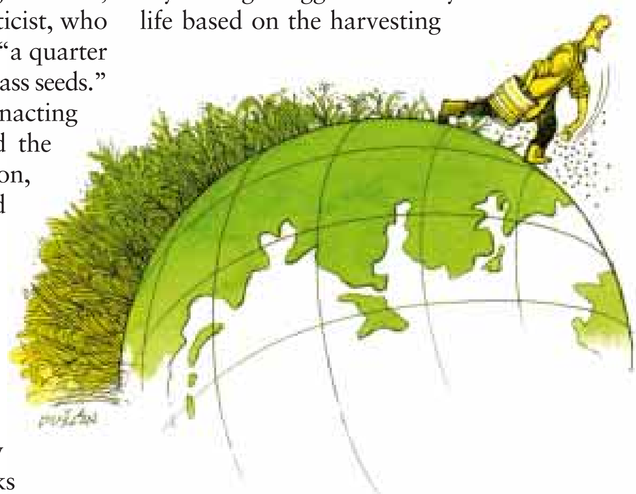
Near the southeast corner of Turkey, gentle basalt slopes many miles wide surround a long volcanic ridge. The land is raw and rocky; patches of soil allow some farming, but livestock graze seasonally on seas of wild grass. Much of that grass cover is in two wild species of the same genus as modern wheat, along with their cross, called wild einkorn. Ten or twelve thousand years ago people hereabouts had been reaping demonstrably similar primitive wheats for sustenance.

There in late summer only 25 years ago, a man walked slowly again and again through the golden stands, a paper sack in one hand, stripping ripe heads with his free hand in the ancient fashion. That collector was no time traveler but an American agronomist, Jack R. Harlan. A crop geneticist, who had spent by his own words “a quarter of a century harvesting wild grass seeds.” Harlan was skeptically reenacting plausible early steps toward the world of cereal domestication, by which we are nearly all fed on grass seeds like a trillion canaries.

His fascinating works and words have for years informed the two of us, enriched our daily bread with a sense of its origins wide and deep, and inspired a few unexpected plantings and tasks for our garden. (We enjoyed raising two of the early domesticates: the bottle gourd and the shiny, hard Job’s tears.)

Harlan’s urbanized bare hands were soon sore, but with a reconstructed ancient sickle, he easily gathered more than two pounds of clean ripe grain per hour of work, its measured protein content higher than that of a modern premium wheat. The difference between harvesting this wild form and modern wheat is chiefly that heads of the wild variety ripen unevenly, so that only a small fraction can be reaped at any given time. Harlan’s harvest proved that archaeological evidence for use of the flint-bladed sickle does not imply domestication.

The wild harvest could be boiled or steamed for porridge. “A family group … working slowly upslope as the season progressed, could easily harvest wild cereal over a three-week span, and without working very hard could gather more grain than a family could possibly consume in a year,” Harlan wrote. “To be sure, cereal pottage would be dull fare,” but assurance of abundant, nutritious food that can be kept for years in dry storage suggests “a way of life based on the harvesting of wild cereals,” with added foraging for variety.



DUSAN PETRICIC

A professor of plant genetics at the University of Illinois for three decades, Harlan found himself becoming something of a time traveler. His field studies took him to 80 countries—“I have not been anywhere that I could not find kindly and helpful people”—to study the major cereal crops of today from the grass roots upward. Fitting genetics and natural history into the archaeological record, he sought with his students the origin of the crops that now nourish us.

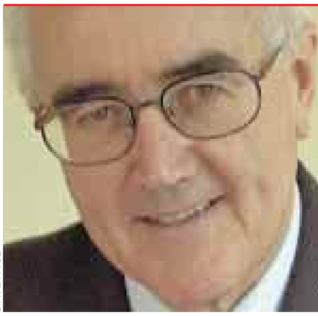
Nearly all myths worldwide suggest that agriculture came as a civilizing blessing, a gift of superior knowledge denied to our untamed and brutish forebears. Only Genesis differs: “In the sweat of thy face thou shalt eat bread.” Modern students of remaining hunter-gatherers rather concur with Scripture. In the harsh Kalihari Desert the foragers worked only some 15 hours a week to win their bread. Of course, the !Kung did not have actual bread nor indeed the need for it: “Why should we plant,” one forager asked, “when there are so many mongongo nuts in the world?”

Only in favorable ecologies did farming offer an escape from disaster—if it did.

When your crop grows wild, you need not clear, plow, sow or even cultivate. One by one the models of the origin of full agriculture fail to explain the facts. Was it a novel discovery? No. The Australians long domesticated their landscape by fire, irrigated plants when the season was dry, and spread out the water in the flood. Other gatherers around the world followed similar practices. Well they knew the life cycle: flower to seed to flower again. As Harlan summed up, “Hunter-gatherers are real professional botanists.…They knew all they needed to take up agriculture at any place.”

Only in favorable ecologies did farming offer an escape from disaster—if it

Continued on page 107

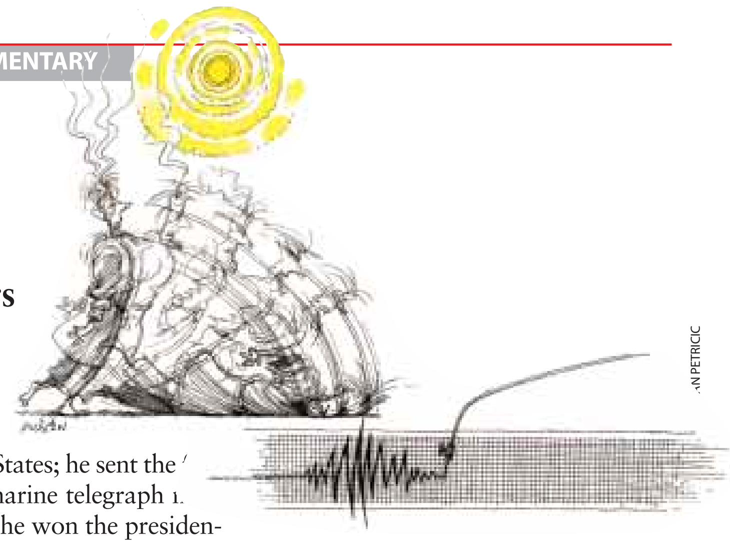


DAVE PAGE

CONNECTIONS

by James Burke

Movers and Shakers



N PETRICIC

As mad dogs and Englishmen are supposed to do, I was out in the midday sun recently, filming a Middle Eastern oil refinery and appreciating why physiologist John Scott Haldane, expert in extreme stress effect, went to Persia in 1936 to investigate cases of heat stroke among the new oil-field workers. Alas, on his return to the chills of Oxford, he caught pneumonia and died. Ironic, in a sense, because he'd also done pioneering work in the field of respiration. In particular, following up (for the British Admiralty) on the experimental work of French physiologist and mimosa expert Paul Bert, who had first identified, in 1878, what we know as the bends. Divers suffer this malady when they surface too quickly and nitrogen bubbles form in the body, causing various symptoms from nosebleed and joint pain all the way to fatal paralysis.

In 1804 Robert Fulton's steamboat reached the breakneck speed of 2.9 miles per hour.

Bert's valuable work came too late to save the sinkers working on the new bridge across the Mississippi at St. Louis. At the time, it was the biggest in the world (and I believe the first to use cantilevered sections to close the span). Now, the problem for the sinkers sinking piers—in the case of the St. Louis structure, digging into soil 100 feet down at the bottom of a compressed-air caisson—was that the men were getting caisson disease (a.k.a. the bends). After two sinkers died in March 1870, the designer of the bridge ordered a slow return to the surface to facilitate more gradual decompression. One James B. Eads.

The "B" stood for Buchanan, the name of Eads's mother's cousin, who was the last U.S. president before the outbreak of the Civil War. James Buchanan had three other main claims to fame. He removed Brigham Young from office to make sure Utah remained one of the United States; he sent the [illegible] transatlantic submarine telegraph [illegible]sage; and in 1856 he won the presidency by beating Millard Fillmore, candidate of the "Know-Nothing" party. Fillmore had already served three years as president, during which time he sent Commodore Matthew Perry and a U.S. fleet to Japan, where Perry signed a treaty that opened Japan to Western trade for the first time. Perry's ship, the *Fulton,* was named after another American hero of the seas, Robert Fulton, who built the first successful steamboat. In 1804 Fulton's initial attempt (on the Seine in Paris) reached the breakneck speed of 2.9 miles per hour. Back in the States, Fulton and his new partner, Robert R. Livingston (formerly U.S. minister to France), tried again, this time using a Boulton and Watt engine. They hit a record 4.7 mph, fast enough to compete with sail. So in 1807 a regular Hudson River steamboat freight service began between New York and Albany.

Livingston was already a well-known figure on the American political scene, having served on the committee that drafted the Declaration of Independence, administered the oath of office to George Washington and last, but far from least, fixed the Louisiana Purchase (by the U.S., of about one third of America, from France). When he sold Louisiana in 1803, Napoleon must have been delighted to get rid of the place in return for $27-million-and-change, because (a) he desperately needed the cash and (b), thanks to an egregious Scottish con man, French Louisiana had earlier bankrupted France, in a scam that made junk bonds look like blue chips. Considering the criminal proceedings that followed the venture's collapse, the Scot whose idea it had been possessed the most unapt name in history: John Law. His rap sheet would've made a great sting movie script: Charged with murder in London. Escaped by filing bars and drugging guards. Fled to the Continent and went upmarket (between 1694 and 1704 gambling himself into a fortune). Went back to Scotland with a devious plan to introduce paper money. Rejected by the canny Scots, returned to the gaming tables and became seriously enough rich for the French to fall for the banknote idea.

Law also met no resistance when he suggested his pièce de résistance: a gigantic investment fund for wannabe millionaires to buy shares in French Louisiana. The territory was glowingly described in Law's sales pitch as being filled with gold and jewels (not there), hardworking locals (not there) and a magnificent capital city (not there). Money flooded in, and the price of Louisiana shares skyrocketed.

Law made himself duke of Arkansas and started building his previously nonexistent capital city of New Orleans. Sooner or later somebody took a closer look and revealed French Louisiana for what it really was: a lot of dirt, trees and water. The entire scheme went down the toilet. So did France's paper-money economy. And the government. Law himself? Long gone to (where else?) the gambler's paradise, Venice.

Early in this checkered career, Law had become buddies in London with Thomas Neale, property developer, master of the English Mint and the official who issued the licenses for gambling houses. In 1694 Neale persuaded the government that he should run various lotteries, and one of the small prizewinners was a coachman who worked for John Evelyn, of diary fame. Evelyn's diary is a highly readable insider's view of the period, the author having been well placed to scribble about who was doing what to whom, because he knew everybody who was anybody. Including an eclectic bunch of weirdos who regularly met at Wadham College at Oxford to talk nerd talk and who inspired Evelyn to suggest they all set up a physico-mathematical experimental college. They did. It became known as the Royal Society.

Apart from these scientific dabblings, Evelyn also wrote the definitive thing on arboriculture, held forth on architecture, collected books and antiques, traveled a lot and did a spot of gardening from time to time. The only small blot on his landscape was when he rented his London house to an Admiral Benbow, who sublet it to a visiting Russian sergeant/carpenter named Pyotr Mikhaylov, who worked at the nearby Deptford dockyards. This guy's idea of fun was to have himself trundled in a wheelbarrow around Evelyn's garden, in the process ruining the flowerbeds. Evelyn said nothing, because the sergeant turned out to be Peter the Great, visiting England on an incognito fact-finding mission so's he could go home and modernize Russia. Which he did. Meantime, during the foreign junket, he left matters at home in the hands of his chamberlain, Prince Boris Golitsyn.

Because the prince had worked behind the scenes to get Peter his throne in the first place, you could say he was quite a mover and shaker. A family trait, given that his descendant (of the same name) would end up as president of the International Seismological Association at their meeting in Moscow in 1911. Boris had been selected for this earthshaking position because he had put Russia in the vanguard of seismology with an electric earthquake gizmo. When a seismic shock caused a small pendulum carrying coils to swing in a magnetic field, the movement induced a current in the coils. Measure the current, and you measured the shock. Golitsyn's seismograph was the prototype of the instruments that would eventually be used to locate those Persian oil fields, whose workers would get heat stroke from all that time spent out in the midday sun. SA

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did. Harlan's wild einkorn crop yielded him an energy output about 50 times his work input; hardly any other system is so good. Was it some Near Eastern accident that started us all off to this grass-fed world with its billions of people, its classes, cities and wars?

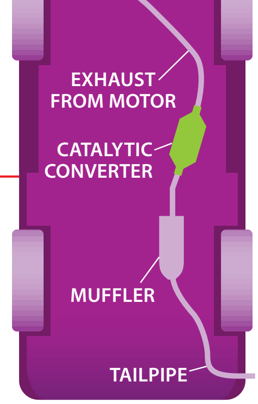
Jack Harlan proposed a "no-model model" for the rise of agriculture. It is clear enough: preadaptation. The foragers had for a long time been able to extend subtle plant-tending to farm whenever they chose. Several staple cereal crops (wheat, maize, rice, barley, sorghum) were taken into full control at about the same time around the world. That change took place when the glaciers last receded. The final step had become so small a one that any modest impetus sufficed. Perhaps somewhere climate forced change by threat of famine; somewhere else new lands opened new opportunity. Once commitment had been made at some scale, the option of abandoning populous villages and ample crops was hardly an open one.

And there were failures: since the collapse of the Old Kingdom of Egypt, in about 2160 B.C., we can point to repeated agriculture instability. For 170 years, no new monuments were built in the land of the Great Pyramids. Did the Nile run low for all that time? One tomb inscription reads: "Everyone was dying of hunger on this sandbank of Hell ... all of upper Egypt.... But I managed that no one died of hunger in this [province]." Thus wrote Ankhtifi, proud monarch of Hierakonpolis. Now we are fed in our billions by the cereal cycle only; our main hedges against failure are our know-how, the global scale, and the huge reserve implied by the ability to divert grain from livestock. Uniformity is painting this diverse world at some gain and at some risk. As vivid old ways fade, "we may find fewer things to quarrel about and a more universal feeling of brotherhood and commonality."

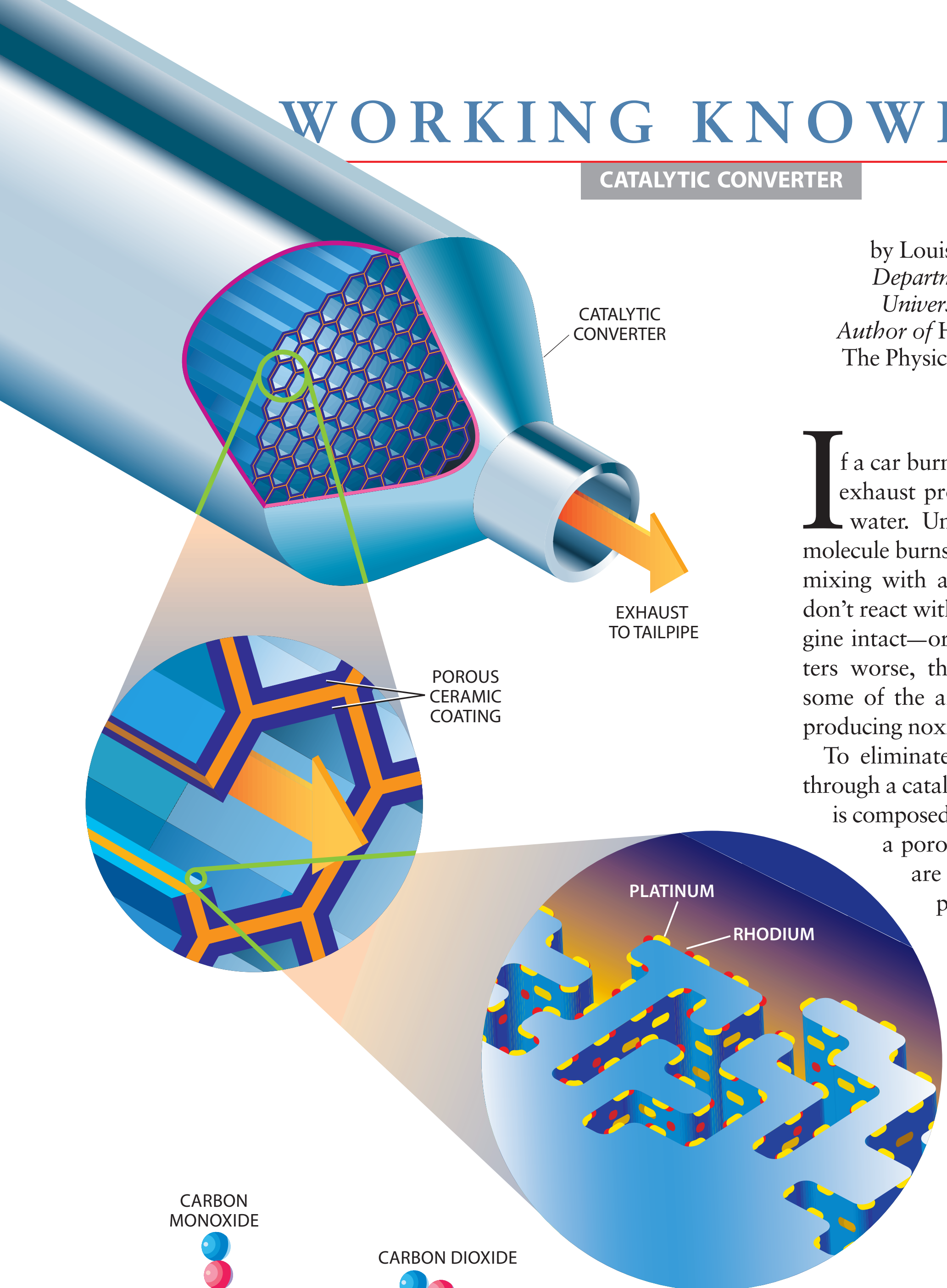
So optimist Harlan wrote in the last lines of his 1995 book, *The Living Fields: Our Agricultural Heritage*. All the citations in quotes here are from that volume, from his 1975 book, *Crops and Man*, or from one of his many papers. When we began our tribute to this engaging, sophisticated and humane scientist so much at home in the global countryside, we had not yet learned of his death in 1998, aged 81. SA

WORKING KNOWLEDGE

CATALYTIC CONVERTER



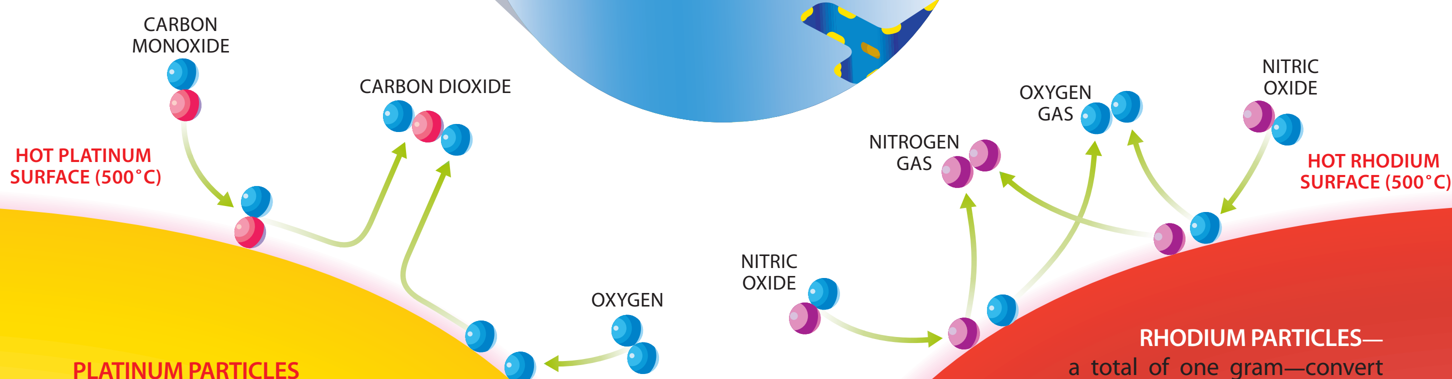
by Louis A. Bloomfield
Department of Physics, University of Virginia
Author of How Things Work: The Physics of Everyday Life



If a car burned fuel with perfect efficiency, its only exhaust products would be carbon dioxide and water. Unfortunately, not every hydrocarbon molecule burns to completion. Because of inadequate mixing with air or just bad luck, some molecules don't react with enough oxygen and thus exit the engine intact—or as carbon monoxide. To make matters worse, the violence of combustion combines some of the air's nitrogen molecules with oxygen, producing noxious nitrogen oxides.

To eliminate these pollutants, exhaust is passed through a catalytic converter. The inside of this device is composed of an array of tubes, each coated with a porous ceramic. Embedded in this coating are tiny particles of two precious metals—platinum and rhodium—that serve as catalysts. Once exhaust heats the converter above 300 degrees Celsius, unwanted molecules bind temporarily to the catalysts and are converted into innocuous chemicals.

ILLUSTRATIONS BY BRYAN CHRISTIE



PLATINUM PARTICLES complete the oxidization of hydrocarbons and carbon monoxide by reducing the energy barriers that normally impede such chemical reactions. Only five grams of the precious metal are needed because the pieces are so small that they offer a large surface area. To ensure maximum combustion, a computer monitors oxygen and fuel levels and carefully balances the two.

RHODIUM PARTICLES—a total of one gram—convert nitrogen oxides back into nitrogen and oxygen. Together rhodium and platinum can remove about 95 percent of the hydrocarbons, carbon monoxide and nitrogen oxides from exhaust. But the converter can be easily damaged. A single tank of leaded gas can coat the catalysts, inactivating them. And overheating can cause the particles to merge, reducing their surface area and activity.