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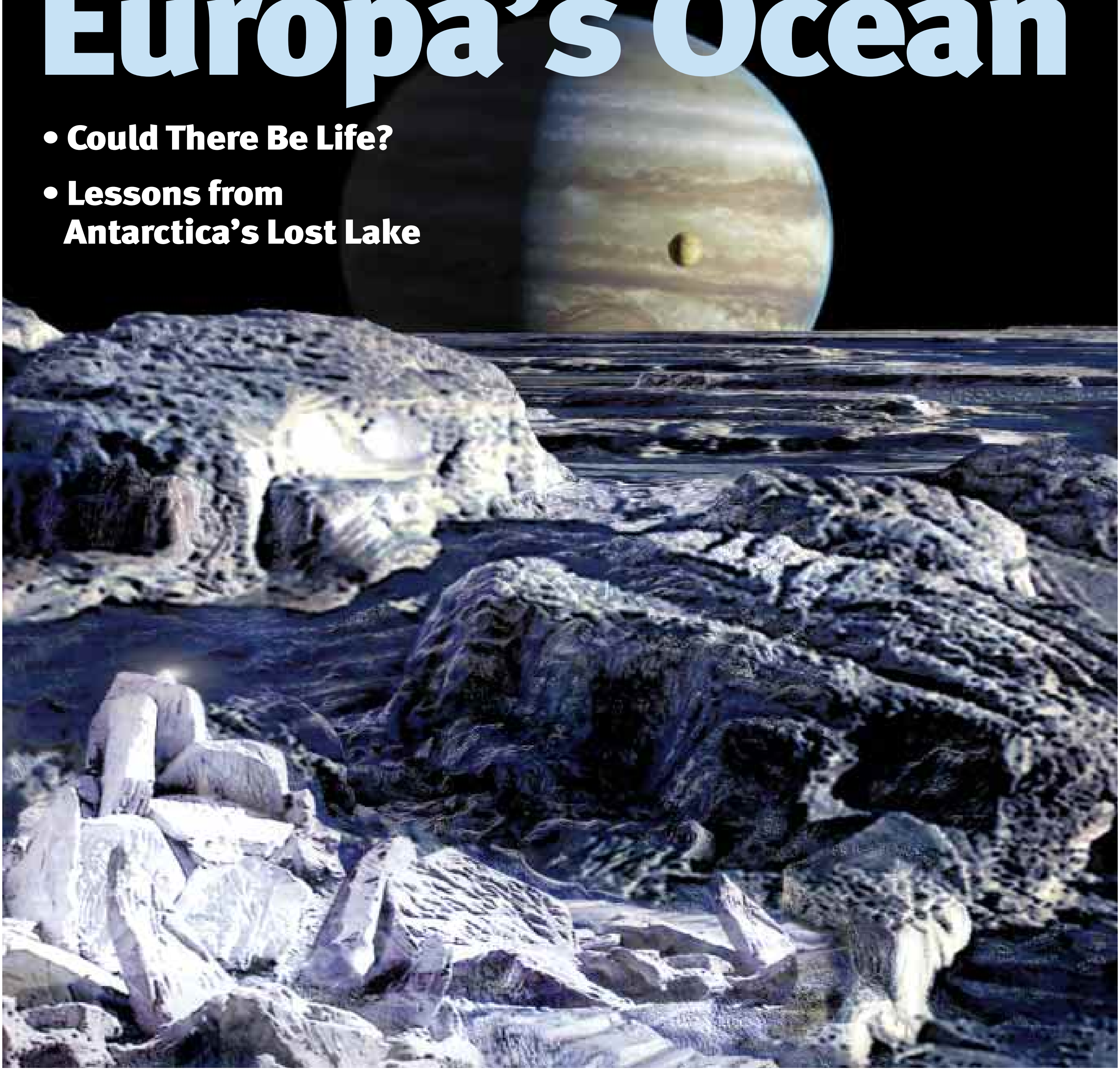
Beneath Its Icy Surface,

Europa's Ocean

- Could There Be Life?
- Lessons from Antarctica's Lost Lake



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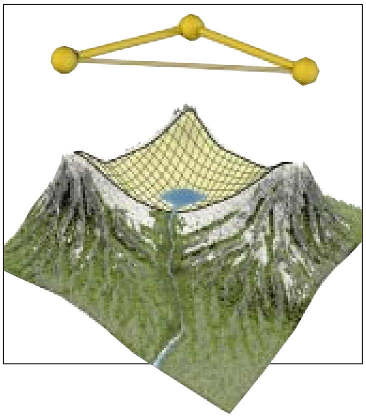

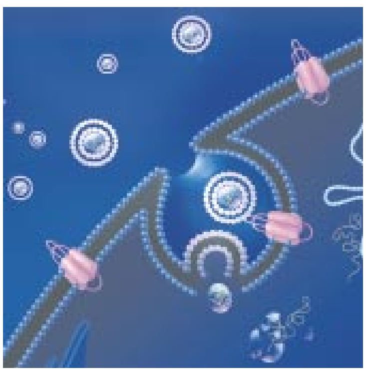

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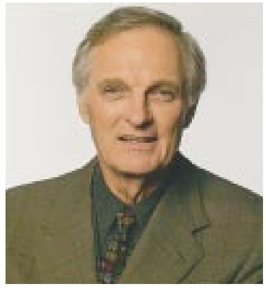
Curiosity and Schrödinger's Cat

This fall the television program Scientific American Frontiers *marks its 10th anniversary. To celebrate it, we invited host Alan Alda to reflect on science and his experiences. The episode "Voyage to the Galápagos" premieres on PBS stations in October; check local listings for times. —The Editors*

Two things in science seem to this nonscientist to be on a collision course. One is the craving to know more. The excitement of pouncing on telltale clues and meaningful patterns can be as thrilling as riding a speeding train. But for a nonscientist, at least, the curiosity train often barrels down a track headed right for this other thing: the Schrödinger's cat thing.



***ALAN ALDA,* *host of* Frontiers**

I don't literally mean Schrödinger's cat. I mean any image whose meaning eludes me because I don't have access to special language.

Sometimes I'm following a conversation with a scientist pretty well, and then, before I know it, boom: Schrödinger's cat. "See? Before the box is opened, the cat is both alive and dead." No, I don't see, actually.

In Schrödinger's thought experiment, a cat in a box whose life depends on certain quantum properties remains both alive and dead until the box is opened. As I understand it, Schrödinger wanted to show that quantum mechanics couldn't be visualized using everyday experience. He certainly did.

A mathematician friend tells me he's hard at work on an article memorializing a colleague. He says, "My goal is to get other mathematicians to understand what he was trying to do in his research, which was powerful but forbiddingly technical." Apparently, even people in the same field can be excommunicated by the expansion of the universe of knowledge and the increasingly weakened signal of specialized language.

This is one reason that I'm so glad *Scientific American* exists and that I've had the good luck to be part of the television program *Scientific American Frontiers*. They both work to bring clarity to some of science's most complex attempts to understand nature—to bring the speeding train of curiosity safely into the Penn Station of Schrödinger's cat, without letting it crash right through.

When I joined the show six years ago, the producers took a chance in letting me interview scientists in a freewheeling way. The interviews are impromptu and allow me to exercise my curiosity. This lets us use playfulness in the pursuit of understanding. Scientists are seen as the fully rounded people they are: smart, funny, creative and especially good at teaching. Our hope is that if I keep asking questions until I actually begin to understand what a scientist is saying, the audience, seeing the lightbulb go off in my head, might also get a spark.

To do this, though, I've had to learn to ask the dumb question—the totally naïve question. Before I learned to do this, my interviews began with my assuming that after reading a couple of research papers, I knew a bit about the scientist's work. The conversation invariably revealed that I pretty much had it all wrong as we went down one blind alley after another. I realize now that assuming I know nothing is much safer and more accurate.

Which brings me back to that darned cat. I'm still trying to get a grasp of Schrödinger's pet without a grasp of the mathematics, which may be impossible. I once summed up my frustration in a fractured limerick:

His cat was both dead and alive
'Til Schrödinger's guests would arrive.
Then he'd open the box.
And toss in some lox—
And the cat would both lay there and thrive.

Now let me ask the naïve question. Will someone out there write a limerick (or even a pair of limericks) that helps me understand Schrödinger's imagery? (Send them to me care of *Scientific American,* 415 Madison Ave., New York, NY 10017, or limerick@sciam.com) The winner will get a *Frontiers* T-shirt and the extraordinary thrill of seeing a lightbulb go off in my head as the train pulls into Penn Station.

ALAN ALDA

LETTERS TO THE EDITORS

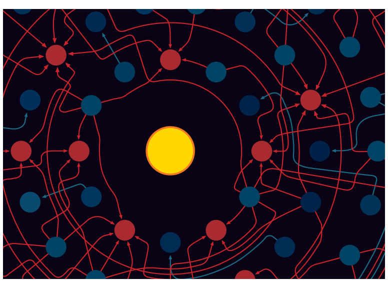
The Wonders column in the June issue ["First Comes the Thunder"] left a bunch of readers, er, *wondering* whether Philip and Phylis Morrison had perhaps erred in their explanation of how a 747 jet stays aloft. "The Morrisons twice state that an airplane's lift is provided by the deflection of airflow downward," notes Jason E. Brunner of Salt Lake City. "I, for one, enjoy flying in airplanes whose lift is provided by the low pressure above the wing created by air moving over and under the wing at different speeds."

The Morrisons agree that Brunner's conventional view of efficient wing flow is correct, but they're sticking by their original assertion, which, they point out, refers to the overall lift of a plane. "Low pressure alone cannot hold things up. For all bodies in flight that have weight, the object is held in flight by an upward force (exerted by the ambient air) that matches the downward force we call weight such that lift is equal and opposite to weight," they explain. "If the air exerts its upward lift, the plane must exert an equal and opposite downward force on the air, which duly moves down and back as the plane proceeds. The overall pattern of flow includes this final flow of departing air (which requires energy from the plane) that satisfies Newton's third law." Additional reader comments regarding the June issue follow.

EVALUATING WEB AUTHORITY

The article "Hypersearching the Web," by members of the Clever project, focuses on the use of hyperlinks to estimate the best Web authorities and hubs. In terms of energy expended, this is indeed efficient and "clever," given that the bulk of the work is done for free by the Web masters, who have a vested interest in making their Web pages as useful as possible. But there are a couple of issues that should be addressed before we accept this method. First, the method relies on human nature in the form of someone deciding to establish a hyperlink. Whether this act is a representation of value is itself a complicated issue. Second, use of the Clever algorithm will, by definition, affect the organization of the Web. As noted in the article, Web masters routinely tailor pages for maximum hit potential. I can easily envision a feedback loop in which Clever develops a set of closely related pages, Web masters note the increased traffic from the related sites and establish more links, Clever tightens the association between the initial pages....

GEORGE A. HARTMAN
Waynesville, Ohio



BRYAN CHRISTIE

AUTHORITIES (●) *are sites that many other Web pages link to regarding a particular topic.*

CROPS AND COMMERCE

I was pleased to see the potential use of plant pathogens as biological weapons being raised as an issue for the 21st century in "Biological Warfare against Crops," by Paul Rogers, Simon Whitby and Malcolm Dando. International commerce, however, presents a far greater danger to the health of our crops than any potential military attack does. The U.S. soybean crop, for example, is under attack by a Southeast Asian soybean rust fungus; and the jarrah forests of southwestern Australia are being wiped out by a Southeast Asian root fungus. Further regulation and monitoring of commercial movement of plant pathogens should be a far higher priority than monitoring possible military uses of these pathogens.

CRAIG M. LIDDELL
Paradigm Genetics
Research Triangle Park, N.C.

LAPSE IN LOGIC?

I am at a loss to understand the double-volume sphere reconstructed from another, smaller one as described in "Gödel and the Limits of Logic," by John W. Dawson, Jr. I propose a simple experiment. Immerse the decomposed pieces in a liquid and measure the volume displaced. By ordinary physics, this has to be that of the original sphere. If the reassembled sphere is now twice the volume, there have to be voids inside it. It is therefore just an ordinary three-dimensional puzzle item and does not require a set theory axiom to explain it.

DENIS P. EDKINS
Lynnfield, Mass.

Dawson replies:

I erred in my description of this theorem. The correct theorem, known as the Banach-Tarski paradox, is that the pieces of a sphere can be assembled into two spheres, each identical to the original. Edkins's proposal, however, is still relevant. Two problems arise if we try to carry out the suggested experiment.

First, the theoretical decomposition of the sphere must involve pieces having infinitesimally detailed shapes, which are impossible to make in a world where solids and liquids are made up of atoms having discrete sizes. Second, the individual theoretical pieces do not have well-defined volumes; only the combinations, put together to form one sphere or two, do. In a hypothetical universe where matter is a continuous material (not made of atoms), if one of the pieces were submerged in an idealized, continuous fluid, mathematics could not tell us what volume of fluid would be displaced.

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 the inset on page 45 ["Mapping the Universe," June], the two maps show the same slice of the universe. All other aspects of the diagram are correct.

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50, 100 AND 150 YEARS AGO

OCTOBER 1949

THE WHITE PLAGUE—"To find a concrete physiochemical basis of tuberculosis virulence, we undertook a comparative study of virulent and avirulent strains of tubercle bacilli, in the hope that we could thereby recognize some specific differences correlated with the ability to cause disease. This comparative approach may lead to the identification of the peculiar structures or properties that permit the tubercle bacilli to establish themselves, multiply and cause damage in the tissues of the body. —René J. Dubos" [*Editors' note: Dubos won a Pulitzer Prize in 1969 for* So Human an Animal: How We Are Shaped by Our Surroundings.]

PLANKTON McNUGGETS—"We would like to believe that in the immense, newly explored organic resources of the oceans lies part of the solution to the world's increasingly acute food problem. Lately we have heard some highly hopeful proposals—that 'farming' of the sea by fertilizer may multiply its yield of fish. Some people suggest catching and using plankton. It is not an attractive food, but it is nutritious, and special processing might make it acceptable. But filtering out a sizable quantity of such small creatures would require an enormous output of energy. By and large we must leave the plankton to the fishes."

OCTOBER 1899

CHICAGO SEWAGE—"If all goes well, in December the waters of Lake Michigan will find a new outlet to the sea through an artificial channel to the Illinois River and the Mississippi. The Chicago drainage canal [*now called the Chicago Sanitary and Ship Canal*] will easily rank as one of the monumental engineering works of this century. The canal was planned as a radical method of solving the problem of sewage disposal for the city of Chicago. The plan involved cutting a great canal thirty-five miles in length and turning the sewage of the city into this vast drainage ditch."

A giant cactus in Arizona

LAST OF HER TRIBE—"Seventy miles off the coast of California lies the small island of San Nicolas, desolate and windswept. Here the wild woman of San Nicolas, Maria Better Than Nothing, lived for twenty years—long enough to forget her people and even her language. Less than one hundred years ago, the Franciscan fathers took the natives—a race of hardy mariners who have left their monuments in large shell heaps and mounds that cover many acres—to the mainland to convert them, except for her. Twenty years after, a priest, with a small schooner named 'Better Than Nothing,' found her sitting in a brush hut, dressed in the skins of birds. Civilization proved disastrous to her, and within three months she died. The sole inhabitant of the island these days is a French herder."

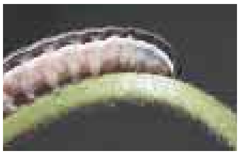
EMERALD BUBBLE—"United States minister to Colombia Charles Burdett Hart writes: 'In July an emerald craze seized upon Bogota. The jewelry stores where emeralds are dealt in were besieged by persons who wished to buy or sell: men and women crowded the streets, and one prominent jewelry establishment was compelled to ask the police to drive the crowd away. Nobody could explain the real cause of the excitement. Now, many buyers who went in on the flood tide find themselves with emeralds that will not bring the price they paid. The only hint of an explanation for this craze is a Bogota dealer who returned from Paris and began to buy emeralds at slightly higher prices.'"

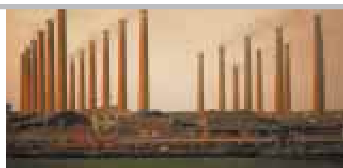
GIANT CACTUS—"Cactus is a genus of plants found chiefly in hot stony places. Their tough, impenetrable skin encloses abundant juice which enables them to support a sluggish, vital action without inconvenience even in parched soil. Our photograph was taken by Mr. A. Messinger, the well-known view photographer of Phoenix, Arizona. The cactus, about 40 feet high, is still standing, although it is slowly rotting and will soon fall. It is 8 miles south of Phoenix, near the Pima Reservation."

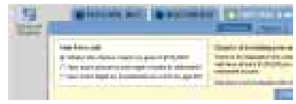
OCTOBER 1849

INDIAN MINERS—"It was discovered in the copper mine diggings at Eagle River, near Lake Superior, in 1844 that the aborigines had extracted the metal from the veins and had made knives and spear-heads of the sheet copper which they obtained. The famous Dr. Jackson searched in nearly all the mines and invariably found Indian stone-hammers. In an interesting description before the recent meeting of the American Scientific Association, he says the stone mining tools betray their true Chippeway origin and are such as all Northern Indians made use of prior to the coming of Europeans. He was convinced that most of the veins now wrought by European and American miners were known and worked by the Red Men, hundreds if not thousands of years before America was discovered by Columbus."

NEWS AND ANALYSIS



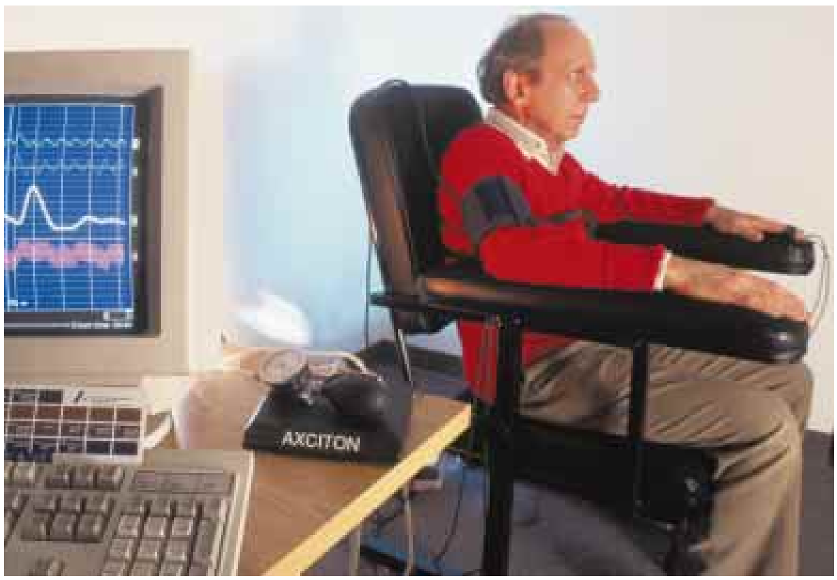




IN FOCUS

TRUTH OR CONSEQUENCES

A polygraph screening program raises questions about the science of lie detection



RICHARD T. NOWITZ *Corbis*

***POLYGRAPH EXAMINATIONS** are in store for many scientists at weapons laboratories. The technique's value for screening is widely disputed, however.*

In earlier centuries, claims of witchcraft may have led to a witch-hunt. Today, in the U.S., the sequence has been reversed. Demands in Congress that someone pay the price for supposedly allowing China to steal nuclear secrets from Los Alamos National Laboratory have prompted the Department of Energy to institute polygraph screening to detect spies at three national laboratories that work on nuclear weapons. The screening will cover Sandia and Lawrence Livermore national laboratories as well as Los Alamos and may extend to as many as 5,400 employees. Testing started during the summer for federal workers and some volunteers employed by the contractors who run the labs. Routine testing of contractors deemed to have access to critical information was scheduled to start in October, after a series of public hearings.

The polygraph, sometimes called a lie detector, has been used for years to screen small numbers of laboratory employees involved in various special programs. Workers have also been able to volunteer to take a polygraph examination in order to accelerate top-level clearance. But the new program would be the first time civilian scientists have been required to pass polygraph examinations en masse to gain, or keep, access to secret information. Because the law does not allow passing a polygraph examination to be a condition of employment, anyone who repeatedly fails will not be fired but shunted into a less sensitive position—and possibly referred to the Federal Bureau of Investigation.

The effort has prompted resentment among laboratory employees because of the dubious science behind most polygraph examinations. According to David T. Lykken, professor of psychology at the University of Minnesota and a recipient of an American Psychological Association career award for service to psychology in the public interest, no published study has ever shown that polygraph screening can detect spies. A real traitor can learn how to fool a screening test, he maintains: the most notorious spy of recent years, Aldrich Ames, passed routine polygraph exams as an employee of the Central Intelligence Agency, as did another former CIA employee and convicted spy, Harold J. Nicholson. Moreover, Lykken's experience indicates that loyal, "straight arrow" types may be particularly prone to fail their tests. Lykken says polygraphic screening is useful only as "a bloodless third degree"—a procedure that deters malfeasance and elicits confessions. But it does so at the cost of wrongfully tainting the careers of some innocent people.

The polygraph works by measuring respiration, heartbeat and conductance of the skin, which supposedly change in response to the stress of lying. Modern versions feed their data directly into a computer, which can then compare responses with a stored database and score results as deceptive, inconclusive or truthful. The Energy Department's screening program employs the "directed-lie" test. Subjects are asked to lie when answering certain "control" questions. (An example of a control question might be "Did you ever steal anything?") Their physiological responses supposedly indicate how they would react if they were to lie deceptively about a crucial question: whether they have ever passed unauthorized information to a foreign national, for instance. Someone whose reactions to substantive questions are judged by officials to be larger than their reactions to directed-lie questions is deemed deceptive.

JEFFREY MARKOWITZ *Sygma*

ALDRICH AMES, who spied for Russia for years, was not detected by routine polygraph exams.

In the only study using the directed-lie test published in a scientific journal, a polygrapher correctly classified as guilty or innocent 80 percent of volunteers in an experiment involving a mock crime. But statistics from mock crime experiments—which computerized polygraphs use to classify responses—cannot be assumed to apply to real-life situations in which careers are on the line, Lykken points out. And volunteers in the published experiment were not asked to try to cheat. Deliberately augmenting one's responses to directed-lie questions by self-stimulation—biting one's tongue or contracting one's anal sphincter, for example—can produce responses that will outweigh those to the important questions, Lykken says. The maneuver thus conceals guilt.

Most of the public discussion about the Energy Department's plan has focused on its probable rate of "false positives"—people incorrectly classified as deceptive. The true rate is unknowable. Some real-world studies of the polygraph rely on confessions to establish validity. But Lykken points out that this approach overestimates the instrument's performance, because suspects erroneously cleared by a polygraph confess less often than those fingered as deceptive. He believes that the directed-lie format is biased against particularly loyal employees who are affronted—and thus respond physiologically—when asked about possible betrayals, even though they answer truthfully.

Los Alamos director John C. Browne has suggested that the proportion of false positives in a counterintelligence screening test would probably be less than 1 percent. The actual number will simply reflect how stringently the interpreters of the test results choose to set criteria for deceptiveness, Lykken notes. Studies based on confessions indicate that when polygraphs are used to test suspects for involvement in specific crimes, the tests rate as deceptive more than 40 percent of subjects who are later positively cleared. Because examiners know they cannot fail 40 percent of those being screened for a sensitive post, they set the hurdles for deceptiveness higher. Still, Lykken guesses that several hundred of the 5,000 personnel now being screened will fail.

Lykken is not opposed to the polygraph in principle: indeed, he supports its use in the so-called guilty knowledge test, which seeks to ascertain whether suspects react to information that only the perpetrator of a crime could know about. In this test, a suspect might be asked, "Was the murder victim wearing a red shirt? Green? Yellow?" But this type of examination, which rests on more plausible assumptions than the directed-lie test, cannot be used for mass screening.

The Energy Department's new head of counterintelligence, Edward Curran, a former FBI counterintelligence official, insists that his program will avoid the pitfalls by employing "the best polygraphers in the business." He says his program will ask only four real questions, all related to spying or sabotage, and no questions about lifestyles (a coded reference to illegal drug use and sexual orientation). Final decisions will be made not by the polygrapher administering a test—whose perceptions might be biased—but by an official at a remote location. The content of the directed-lie questions will be negotiated on a case-by-case basis, he states.

Asked about the possibility that spies might trick the test by self-stimulation, Curran says he has "never seen it work yet." He hotly denies that the polygraph failed to raise suspicions about Ames: the polygrapher in that case made errors, Curran maintains, because subsequent examination of Ames's polygraph charts shows evidence of deceptiveness. Although the Department of Defense has funded research on other types of physiological screening, such as thermal imaging, voice-stress analysis and pupil dilation, Curran says there are no plans to use these exotic detection schemes in the new program.

Other agencies, notably the FBI and the CIA, already use the polygraph routinely to screen applicants for employment, and some who failed their examination have protested loud and long that they are victims of an injustice. It seems likely that some scientists will now be joining them—victims of a science that the late Senator Sam J. Ervin of North Carolina likened to "20th-century witchcraft."

—Tim Beardsley in Washington, D.C.

ECOLOGY

PIRATE FEAR

Controversy heats up about chlorfenapyr, a.k.a. Pirate—a pesticide some claim is the next DDT

After 20 years of repeated sprayings of the pesticide Malathion, the boll weevil no longer rules the nation's cotton fields. But in its wake, beet armyworms—moth larvae so named for their ever widening swath of destruction—have gained fame for their ability to reduce weather-toughened cotton farmers to tears. The key to the plague was an unintended casualty of Malathion: the wasp that preys on armyworms. "It's unbelievable," says Auburn University ornithologist Geoffrey E. Hill. "I've literally seen them strip a field. There's nothing left."

Mississippi farmer Philip Barbour knows that. The infamous 1995 infestation annihilated his crop, along with those of farmers in south Texas, the Mississippi Delta and points east. "In 1995 there were so many, they were crawling up telephone poles," he recounts. With no effective pesticide, Barbour lost his shirt along with his crop.

Enter chlorfenapyr, trade name "Pirate." It belongs to a new family of compounds called pyrroles. Its manufacturer, American Cyanamid, based in Parsippany, N.J., with manufacturing headquarters in Hannibal, Mo., wants Environmental Protection Agency approval to use Pirate against beet armyworms. Some 30 other nations, including Australia, China, South Africa, Zambia and Zimbabwe, already use it; Canada and the European Union have pending applications. The company hopes eventually to expand Pirate's deployment beyond cotton to other crops, including vegetables and fruits.

Yet some scientists see an ecological disaster in the making: chlorfenapyr, they insist, is the next DDT. Like that infamous compound, chlorfenapyr, opponents argue, can be consumed by an animal and accumulate in its body, disrupting the endocrine system and harming reproductive abilities. The controversy has exploded in recent months, after the American Bird Conservancy, an advocacy group, issued an "action alert" over the Internet. In response, letters for and against the compound flooded into the EPA. The issue comes in the midst of the political flurry stemming from the EPA's move in early August to ban methyl parathion and azinphos methyl—two widely used pesticides that can affect human nervous systems.

Inactive until consumed, chlorfenapyr kills by interrupting the manufacture of the energy storage molecule ATP in cells' mitochondria. The action of chlorfenapyr depends on several of the ATP cycle's enzymes, which are common to all living organisms. The company says, however, that only insects have adequate amounts of the necessary enzymes to be affected; most organisms will be safe.

It is this action on the ATP cycle that worries so many scientists. They agree that chlorfenapyr varies greatly in its effects on living organisms but are concerned because the reasons for the variability are poorly understood. To date, the EPA has adamantly declined to grant general permission. Citing the compound's soil half-life of 1.4 years, the EPA's risk assessment concludes: "Terrestrial wildlife dietary residues associated with all label application rates present a substantial risk to avian species for both acute lethal effects and impairment of reproduction."

Nevertheless, American Cyanamid has already positioned Pirate throughout the U.S. cotton belt as the product of choice for armyworms. The efforts of a handful of politicians led to permits for "emergency" use in 11 states. Cyanamid spokespersons would not confirm that the company has already invested a rumored $100 million in the chemical but did say that that figure would not be "unusual."

No one disputes the toxicity of chlorfenapyr. In an EPA-mandated lab study by American Cyanamid, mallard ducks were fed 2.5 parts per million of chlorfenapyr—an amount an EPA official stated was close to the residue left in the wild. That group laid 30.13 eggs, compared with 50.75 for the control group, and the hatching rate was 48 percent, compared with the control's 65 percent. The final average weight of adults was also lower.

Opposition is legion. In a statement to the EPA, developmental neurotoxicologist Diane S. Henshel of Indiana University asked, "Do we really want to risk this again, and with a chemical clearly more acutely toxic to wildlife than is DDT?" Analytical chemist Edward L. Sones, who works for a German household products company that does not compete with American Cyanamid, says he has prepared many EPA risk assessments and adds: "I would never consider even continuing research on compounds representing this level of environmental hazard." The U.S. Fish and Wildlife Service stated that Pirate presents "an unacceptable risk by adversely affecting birds, fish, aquatic invertebrates and insect pollinators." When contacted for this story, many officials from government bodies, such as the Canadian Wildlife Service and the U.S. Department of Agriculture, echoed the sentiment.

RICHARD HAMILTON SMITH *Corbis*

***COTTON FIELDS** have become the battleground between makers of a pesticide called Pirate and ecologists who fear it may severely harm wildlife.*


NORM THOMAS *Photo Researchers, Inc.*

BEET ARMYWORM is Pirate's target.

Mark W. Atwood, president of Cyanamid's global agricultural products research division, calls such fears vastly overblown, arguing that many commenters had not considered "the whole package." With Cyanamid's permission, the EPA posted relevant documents on the Internet (www.epa.gov/opprd001/chlorfenapyr/toc.htm). Atwood says, however, the EPA provided only those documents supporting its case and left out those supporting the company's.

Cyanamid executives charge that the method by which the EPA extrapolates lab data to "real world" situations is skewed toward excessive caution. They say wildlife will never ingest or bioaccumulate enough toxin to cause problems if the chemical is used correctly. Current instructions, for instance, tell farmers to leave buffer zones—edges of fields that should not be treated and that will mitigate the risk to birds, according to Atwood. Comparison to DDT, they maintain, is sensationalistic. Scientists and agencies "didn't look at all the database that was available," Atwood says. "They have focused on the toxicity component and have not focused at all on the exposure side." The chemical has been used worldwide for several years, but no one has documented wildlife kills, he points out. In support, ornithologist Hill wrote the EPA, saying that in his Cyanamid-funded study of fields treated with Pirate, he found no dead birds. "When the data are considered in totality and with the real world exposure information, Cyanamid believes that chlorfenapyr should be granted registration," Cyanamid assistant vice president Rebecca Rasmussen said in a statement.

"You're looking for an effect that you might not see for years," counters the EPA's Susan H. Wayland, the official responsible for making the final agency decision. "The concern about birds is… that there will be an impact on their ability to reproduce." Many observers express anger over political tactics they say are meant to pressure the EPA. Senator Trent Lott of Mississippi called Wayland into his office, requiring her to answer Cyanamid executives' questions. Atwood denied that the meeting was meant to pressure EPA employees. For her part, Wayland says that the emergency permits were not the result of Lott's actions but of the needs of cotton farmers.

Complicating the issue is the purported efficacy of other products. The EPA lists several forthcoming alternatives that it claims work as well as chlorfenapyr and are substantially less toxic, such as spinosad, a new class of pesticide made by Dow Chemical. But whether any can replace chlorfenapyr has been debated. Chip Morgan of Mississippi's Delta Council, representing about 500 cotton farmers, says no one compound will be the magic bullet. How well a chemical works depends on many factors, including field conditions and the point in the armyworm's life cycle when the pesticide is applied.

Meanwhile, in an ironic twist, this year's cotton harvest looks like the best in a long time—and prices are the lowest in 24 years, making some lenders "very, very nervous" about farmers' ability to repay their debts, Morgan notes. That insecurity might make growers more apt to use powerful pesticides as a means to ensure a profitable yield.

Given the high stakes, what are farmers like Philip Barbour, who has 900 acres of cotton, going to do? "Pirate is a good product," he declares. "I'm not afraid of it. You just have to choose who to believe." *—Wendy Williams*

WENDY WILLIAMS, a wildlife journalist based in Cape Cod, described the species-threatening turtle trade in the June issue.

PHYSICS

QUANTUM DÉJÀ VU

In an exquisite "quantum nondemolition" experiment, physicists see a single photon and then see it again

The microscopic quantum world where Heisenberg's uncertainty principle rules can seem a bit like Heraclitus's river, made all the more mercurial by the river changing course every time you so much as look at it. Try to observe the same quantum particle a second time, and chances are you'll find your first measurement has knocked it about. Individual photons, the quantum particles of light, would seem to be an extreme case in point: the standard ways to detect a photon involve its complete destruction when it is absorbed by, say, a retina, camera film or photomultiplier tube.

But now Serge Haroche, Jean-Michel Raimond, Michel Brune and co-workers at the Ecole Normale Supérieure in Paris have carried out an experimental tour de force by catching an individual photon in a box, detecting it in a way that leaves it in the box and then detecting it again. The result is the first demonstration of a "quantum nondemolition" (QND) measurement on a single particle.

The idea of QND measurements was devised in the 1970s by physicists wanting to detect gravitational waves, which would induce tiny vibrations in huge cylinders of aluminum. Conventional schemes would have obliterated the signal with quantum noise generated by the measurement itself. Heisenberg's principle can't be repealed, but the trick of QND is to ensure that the inevitable disturbance doesn't contaminate the particular quantity being observed.

In the field of quantum optics QND has flourished and matured since the mid-1980s. QND measurements have been performed on laser beams, typically by using a second probe beam to observe quantum properties of the first beam without disturbing those properties. Such beams contain millions of photons; what can be used as a probe when the target of interest is but one photon? Haroche's answer is a single, carefully prepared atom of rubidium.

In the Paris experiment, much of the activity takes place inside an enclosure formed by two dishlike niobium mirrors about 2.7 centimeters (1.1 inch) apart. Microwave photons with a wavelength of six millimeters bounce around between the two mirrors, which are cooled almost to absolute zero.

Each probe rubidium atom is excited to a Rydberg state, one in which the atom's outermost electron orbits far from the remainder of the atom. The particular Rydberg state is chosen so that when the atom passes through the cavity with a photon present, the atom and photon form a strongly coupled system in which all the photon's energy oscillates back and forth between the atom and photon. The Paris team sends the atom through the tiny enclosure at precisely 500 meters per second (about 1,000 miles per hour), a velocity chosen so that by the time it exits on the other side, exactly one atom-photon oscillation will take place if exactly one photon is present.

Because one whole oscillation takes place, no net energy transfer occurs, meaning the atom does not absorb the photon but leaves it behind in the cavity. The interaction does change the phase of the atom—if the atom is thought of as a wave, the wave's peaks are swapped with its troughs. This phase change is detected by means of an interference effect. To verify the nondemolition aspect of the measurement, the physicists send two atoms through in succession and see how often the atoms agree on the number of photons present. Wojciech H. Zurek, a quantum-mechanics expert at Los Alamos National Laboratory, says that "the sheer ability to manipulate three quantum systems and to control the manner in which they 'talk' to one another with this precision is stunning."

Other experiments are made possible by the single-photon QND apparatus, including the so-called quantum entanglement of three atoms by passing them through the cavity one at a time. Such systems could be used for dramatic new demonstrations of the essential quantum nature of reality. *—Graham P. Collins*

RESEARCH INTEGRITY

FAT IN THE FIRE

A researcher found to have faked data on electromagnetic fields says it's all a misunderstanding

Findings that a biochemist faked experimental results in two published papers have devastated research on possible effects of low-intensity electromagnetic fields. The Department of Health and Human Services's Office of Research Integrity has released a draft of an analysis concluding that Robert P. Liburdy, a biochemist who worked at Lawrence Berkeley National Laboratory until he was forced to retire this year, "intentionally falsified data" to show that such fields affected cultured cells. The assessment concurs with a committee at the Lawrence Berkeley laboratory that found Liburdy had engaged in scientific misconduct. Liburdy, the committee said, "deliberately created artificial data where no such data existed" and sat on data that contradicted his published claims.


NAJLAH FEANNY *SABA*

POWER LINES emit fields, but their effects on cells are questionable.

Liburdy published the scientific papers at issue in 1992. Graphs in the papers purport to show that 60-hertz electromagnetic fields, such as those emitted by power lines and electrical devices, alter the movement of calcium ions through channels in the membranes surrounding cultured cells. Because calcium ions are an important biological signal, the results suggested how fields might influence cells and perhaps cause illness.

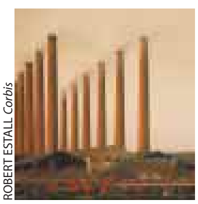
Shortly after the papers were published, an unnamed whistle-blower made a complaint, thus triggering Lawrence Berkeley's investigation. The government followed with an "oversight review," because Liburdy had received federal grants (totaling almost $6 million between 1990 and 1999). Lawrence Berkeley says it has returned to the government the only portion that was not spent, $360,858 from the National Institutes of Health. The Department of Health and Human Services has reached an agreement with Liburdy that says he will not formally contest the government's findings or receive federal grants for the next three years. The agreement states that Liburdy neither admits nor denies misconduct but stipulates that he will retract the published figures at the center of the affair.

According to the government's detailed analysis, in one paper Liburdy presented only 7.1 percent of data points to support his theory and fabricated read-

IN BRIEF

A Model Tumor
About 15 years ago scientists induced normal mouse cells to become cancerous; now they have finally repeated the trick with human cells. In the July 29 *Nature,* a team led by Robert A. Weinberg of the Whitehead Institute in Cambridge, Mass., report creating human tumor cells by adding three genes: a telomerase gene, which allows the cell to grow and divide indefinitely; an antigen that turns off the signals that keep cell growth in check; and a cancer-causing gene called *ras*. The discovery elucidates pathways of tumor formation and may lead to tests that predict whether a benign tumor will become malignant. *—Christina Reed*

A Less Carbonated Earth
Global emissions of carbon dropped 0.5 percent in 1998, to 6.32 billion tons—even though the world's economy grew 2.5 percent. The estimates, from the Worldwatch Institute, suggest that economic expansion need not be a casualty of stricter environmental rules. The drop stemmed from tougher standards and subsidy removals, which led to improved energy efficiency and less coal use. And according to a study released by the World Wildlife Fund, aggressively curbing greenhouse gas emissions could create 870,000 new jobs in the U.S. and save the country $43 billion annually. *—Philip Yam*


ROBERT ESTALL *Corbis*

Smoking less

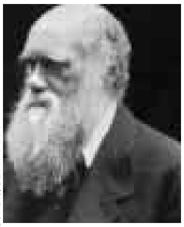
Freshwater Cool
Researchers say in the July 22 *Nature* that a massive discharge of freshwater produced the greatest chill in the past 10,000 years, cooling Greenland by as much as eight degrees Celsius (4.4 degrees Fahrenheit) and western Europe by 3 degrees C. The scientists propose that two glacial lakes dammed behind a remnant of the Laurentide Ice Sheet burst through when the ice melted. The freshwater acted like a blanket over the denser salt water of the Labrador Sea, altering circulation and preventing ocean heat from escaping into the atmosphere. The cold spell lasted from 8,400 to 8,000 years ago. *—C.R.*

More "In Brief" on page 34

In Brief, continued from page 32

Charles Darwin Out

In a nod to creationism, the Kansas Board of Education voted in August to eliminate nearly all mention of evolution in the state's science curriculum. Though not banned in the classroom, Darwinism will not appear on state exams; teachers may therefore avoid the subject. Kansas joins Alabama, New Mexico and Nebraska in challenging evolution, and in a first, it also deletes reference to cosmology's big bang. In response, some state legislators hope to change the school board from an elected body to an appointed one; Fred Spilhaus of the American Geophysical Union has called on scientists to become more active on local boards. *—P.Y.*



CORBIS/BETTMANN

Not in Kansas anymore

Seeing the Depressed Brain

Using positron-emission tomography, Joseph Wu of the University of California at Irvine and his colleagues report in the August *American Journal of Psychiatry* that depressed patients who felt better after sleep deprivation—long known to briefly alleviate symptoms of clinical depression in 30 to 50 percent of cases—showed unusual metabolic activity in three areas of the cerebral cortex connected to the regulation of emotion: the anterior cingulate, the medial prefrontal cortex and the posterior subcallosal cortex. The information may lead to new and better-targeted antidepressants. *—P.Y.*

New and Not Improved

Not that shoddiness pays off, but according to Roland T. Rust of Vanderbilt University and his colleagues, low quality may actually increase the chance a customer comes back. Based on behavioral experiments, the researchers write in the June issue of *Marketing Science* that the expectation of quality is not the only factor in buyers' choices; the amount of risk associated with a brand also plays a role. Evidently, patrons aren't turned off by inferior service if they expect it in the first place. Promotions and trial periods may be more effective than just advertising, and paying attention to loyal customers can be counterproductive, because exceeding their expectations isn't needed to increase preference. *—P.Y.*

ings to make it look as though the "noise" in his data was much smaller than it really was. He invented one result and failed to process other data as he described. In the other paper he algebraically manipulated results to create an apparent effect where none existed and made up data to conceal the manipulation. The attempts at concealment rule out honest error, the Research Integrity Office concludes, which charges that Liburdy also misstated his techniques in grant applications.

Liburdy denies any misconduct, blaming everything on a difference of opinion. He cites three independent scientists whom he asked to review his work and who concluded in 1995 that he was not guilty of misconduct. But the Office of Research Integrity reports that Liburdy sent these experts information contrived to conceal his methods. One of them, James Putney of the National Institute of Environmental Health Sciences, tells Scientific American that Liburdy asked him to comment on just one figure and that he never saw Liburdy's raw data. (Even so, he judged the figure to be "clearly improper.")

Liburdy maintains that his scientific conclusions stand and notes that an earlier finding of misconduct by the Office of Research Integrity, involving Nobel laureate David Baltimore, was thrown out by an appeals court. Liburdy protests that the government's investigation was unfair because it examined his data with software unavailable to him back in 1991; he agreed to withdraw his graphs because he could not afford a protracted legal battle, he says.

Some workers in Liburdy's field who have not read the government's probe declare they cannot believe that he acted as it concludes. But the taint may mean that they will be held to more exacting standards in the future.

—Tim Beardsley in Washington, D.C.

COSMOLOGY

BOOM OR BUST?

New doubts about whether cosmic expansion is accelerating

They may be halfway across the universe, but distant supernovae have caused quite a ruckus on the earth. Two years ago astronomers discovered that these stellar explosions are dimmer than expected—so much so that the very structure of space seemed to be responsible. Their anomalous dimness intimated that the expansion of the universe may be speeding up rather than slowing down, as cosmologists had always assumed. But now several of the supernova observers worry that their dramatic findings, like some other disputed claims, jumped the gun. Adam G. Riess of the University of California at Berkeley says grimly, "I liken it to the discovery of life in the Mars rock."

The argument for cosmic acceleration depends on two key measurements for each of several dozen supernovae: the maximum brightness of the explosion, which shows how far away it is and hence when it took place; and the redshift, which records how much the universe has expanded since it occurred. The farthest known supernovae went off 8.4 billion years ago, and since then the universe has doubled in size. Yet at its current expansion rate (as inferred from more recent supernovae) the universe would have tripled in size. Therefore, the expansion rate must have increased.

All this hinges on differences in brightness of about 25 percent. As it happens, supernovae of the type used by cosmologists naturally vary by about the same amount, probably because of differences in the mass and composition of the stars that give rise to such explo-

BRIAN P. SCHMIDT *Mount Stromlo and Siding Spring Observatories (left and right);* CHUCK FARANDA *(center)*

***SLOWLY BRIGHTENING SUPERNOVA** in a relatively nearby galaxy—as revealed by photographs before the explosion began* (left), *one day after* (center) *and at the maximum brightness* (right)*—has cast doubt on observations of more distant supernovae.*

sions. This diversity once made supernovae too unpredictable to serve as gauges of distance. But in studies of nearby supernovae, observers noticed that the brighter they are, the slower their glowing embers fade over time. By measuring the rate of fading, observers can now compensate for the variations. Their only assumption is that this procedure also works for faraway supernovae.

Which is what Riess and his colleagues have recently called into question. The team, a subset of the High-Z Supernova Search, one of the two main groups examining supernovae in a cosmological context, looked at a hitherto neglected attribute of the explosions: the time it takes them to attain their maximum brightness. They spied 10 nearby supernovae and tracked their brightening, in one case using a photograph taken by amateur astronomer Chuck Faranda of Fort Lauderdale, Fla., about a day after the blast began—one of the earliest images ever made of a supernova.

The researchers determined that the nearby supernovae typically took 20 days to reach peak brilliance. By comparison, a group of far-off supernovae—reported earlier by the other main group, the Supernova Cosmology Project, based at Lawrence Berkeley National Laboratory—took only 17.5 days. Therefore, it seems that stellar explosions unfold differently depending on how long ago they occurred.

Persis S. Drell and his colleagues at Cornell University have raised another warning flag: different formulas used to compensate for the natural variation in supernovae, each purporting to calculate the true brightness of the explosions, generate slightly different values.

Many theorists think these discrepancies don't matter. The brightening time depends on the early stages of the explosion, when details make the most difference. But the maximum brightness and fading rate—the only two things cosmologists care about—involve the gradual release of energy by the debris, which should be largely independent of the characteristics of the late star. Other researchers are less sanguine. The disparities might be the dead canary in the coal mine, indicating that the theory is awry even if nobody knows quite why.

Alternatively, the discrepancies might indicate that acceleration is merely an artifact of observational biases. Andrew Howell and his colleagues at the University of Texas in Austin have pointed out that distant supernovae have been discovered with electronic detectors, whereas nearby ones have mostly been found on photographs. Film tends to overexpose the center of galaxies and so miss any supernovae there, thereby skewing the sample and undermining the procedure that compensates for supernova diversity. But by the same token, selection effects may have led Riess's and Drell's teams to find problems where none really exist. Only new studies, designed specifically to avoid such biases and to check whether near and far supernovae are indeed comparable, will resolve the issue.

So was it premature to trumpet the accelerating universe as a revolution in cosmology? Not necessarily. Other pillars of evidence, such as the cosmic microwave background radiation and estimates of the total amount of matter in the universe, remain unshaken. "The supernova evidence was never, in my view, the best evidence for cosmic acceleration," says cosmologist Paul Steinhardt of Princeton University. "The arguments we already had are much more solid." *—George Musser*

EARTH SCIENCE

DESERTING THE SAHARA

Dying plants harvest harsh surprises from climate change

Plants may seem to sit passively as climate decides their fate, but scientists are beginning to believe that vegetation can strongly amplify the climate's most subtle whims—sometimes with abrupt and devastating results. A new computer simulation indicates that plants helped to turn the Sahara from a lush grassland thriving with hippos and elephants to its current condition as the world's largest desert.

The Sahara's succulent sojourn faced an abrupt end about 5,500 years ago. In a matter of centuries, rainfall levels plummeted, the green grasslands paled to a sandy yellow, and civilizations were forced to relocate. Many scientists have assumed that human beings, who arrived there 7,000 years ago, overused the land, which led to the quick loss in vegetation. But the new simulations show that a steady but slow loss of grasses—stemming from a gradual trend toward less rainfall beginning about 9,000 years ago—ran wildly out of control.

"Climate modelers tend to think that vegetation is not important, because it's only about 20 percent of the planet's surface area," says Martin Claussen, leader of the team that designed the simulation at the Potsdam Institute for Climate Impact Research in Germany. "We're now seeing that we're not allowed to neglect land area."

John E. Kutzbach, a climatologist at the University of Wisconsin–Madison, is enthusiastic about the results because of their value in predicting future climate. "The idea that vegetation affects climate hasn't been studied in detail," he says.

Both Kutzbach and Claussen had independently used earlier computer simulations to watch how local weather affected Saharan plants, but Claussen's latest simulations allowed his team to be the first to see whether the plants themselves might effect change. Each of the team's 10 simulations began with the grasslands of 9,000 years ago and ended with the arid desert of the present.

The only external force they introduced to their simulated climate was a


IFA Peter Arnold, Inc.

AFRICA'S SANDY SAHARA was once a green, thriving grassland.

gradual evolution of the planet's orbit. About 9,000 years ago the earth's perihelion, the point at which the planet passes closest to the sun, occurred in July, and the North Pole was leaning more toward the sun. These two circumstances, which then meant stronger summer sunlight for the Northern Hemisphere and thus stronger monsoons to water a thirsty Saharan grassland, have changed slowly ever since. The northward tilt has shifted away from the sun, and perihelion now occurs in January.

During the first few thousand years of Claussen's simulation, this transition manifested as a gradual loss of vegetation, presumably because the monsoons were weakening. But the grassland's condition took a dramatic nosedive starting about 5,500 years ago, the same time that lakes and large animals begin to disappear from the fossil record. The team speculates that the grasses of the early Sahara trapped moisture that could evaporate and become new clouds—and new rain. As desert sands took over, less water recycled to the atmosphere, so even less rain fell and more plants died. "We can now explain the most important changes in Saharan climate without taking human beings into account," says team member Claudia Kubatzki.

Kutzbach says that the findings of Claussen's group "open up a research area rather than being the final word," but he agrees with their theory that a vicious feedback cycle between vegetation and the atmosphere could force dramatic changes. More specifically, the role that plants play in their own sustenance can be key to their destruction.

Just because the Sahara apparently dried up because of natural causes does not mean that humans are off the hook. Noting that as much as 30 percent of the rainfall in a tropical rain forest has cycled through the leaves and roots of its flora, Kutzbach and his colleagues suggest, based on their own climate simulations, that cutting down trees could produce a feedback cycle similar to what the earth's changing orbit set off in the Sahara. "If you deforest, the rain washes down the Amazon rather than going back into the clouds to form rain," Kutzbach says. And pumping ever more carbon dioxide and other greenhouse gases into the atmosphere may do more than slowly warm the planet.

"We can't specify what will happen," Claussen says, "but we're assessing the danger of climate surprises."

—Sarah Simpson

ANTI GRAVITY

It's Not Oeuvre Till It's Oeuvre

You can observe a lot just by watching, according to one of the foremost neurolinguists of our time, Lawrence Peter Berra, known as Yogi to his many disciples. If you've been watching the news, you may have observed the music of Mozart getting a lot of attention in recent years as a brain enhancer. For more than half a century, Yogi has endured ballpark organs playing the decidedly non-Mozartian ditty, "ta ta ta TA ta TAAAA," which implores the fans to then scream "charge." But because Yogi also wondered, "How can you think and hit at the same time?" he probably didn't cry foul at the lack of any brain-building melodies emanating from stadium loudspeakers.

MICHAEL CRAWFORD

Turns out he probably wasn't missing anything (especially high fastballs). A study in the July issue of the journal *Psychological Science,* from Kenneth Steele and his colleagues at Appalachian State University, disputes those isolated previous findings indicating that a few minutes of Mozart, specifically the Sonata for Two Pianos (K. 448), raise the spatial reasoning capacity of test subjects, albeit temporarily. The attention paid to the so-called Mozart effect helped to pave the way for some pregnant women to slap headphones on their swelled bellies, so that the symphonic could mix with the amniotic to induce the mnemonic and other brainy stuff. Additional histrionics could be found in Georgia, where all new mothers now get classical CDs as a public health measure.

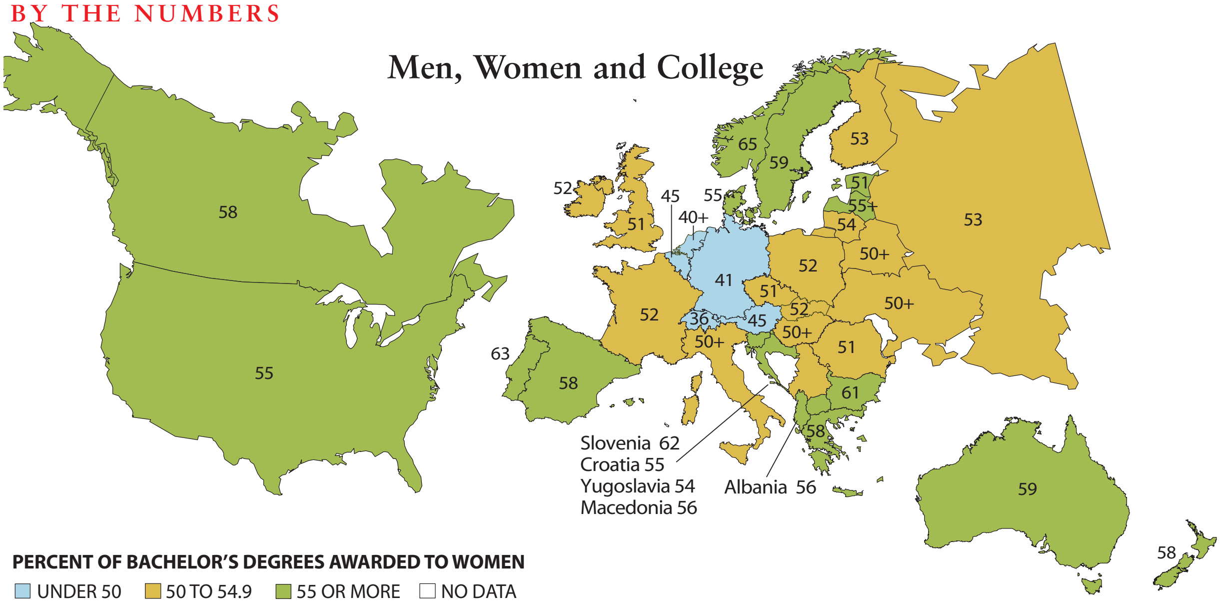
Now, I admire Mozart as much as the next guy, especially if the next guy is Salieri. (I've even had the privilege of playing some Mozart—K. 622, for you fans keeping a score at home.) But those earlier studies, even had they been verified, were still quite limited. They only looked at that one Mozart composition and only compared its effects to silence and to a work by the minimalist composer Philip Glass, who sometimes puts me into a lovely trance state and sometimes makes me seek out the hardest flat surface I can find so I may, rhythmically and repeatedly, bang my head. So, bottom line, listening to Mozart probably doesn't make you smart. In fact, it's usually the other way around.

In other news showing that a little data may go a long way, the American Academy of Pediatrics issued a report in August recommending that children under the age of two be shielded from the corrosive effects of television by being totally prohibited from watching it. (The new Mozart study does away with the awkward conflicts that would have been posed by televised productions of *Don Giovanni*.) The lead author of the report admitted that hardly anything is known about TV's effect on kids two and under. But she justified the ban by noting that the known requirements for proper brain development—you get smart from a bonanza of good times with all in the family—have less of a chance of happening if the baby's butt is parked in front of the tube all day. She's probably right, although it would be ironic if 30 years from now research were to show that the adults best able to function in a world where most communication of information is taking place on video screens were precisely those who learned to program the VCR before they could walk to the mailbox to get the *TV Guide*.

So what's a parent to do? Keeping a child away from unhealthy influences is an obvious and heartfelt desire. On the other hand, Mom eventually has to do the laundry. (I'm not being sexist—we all know that it's Mom who does the laundry.) If Barney keeps the little guy happy for the time needed to hang up the fine washables, will Mom disregard the pediatricians' recommendation? The contemplation of this kind of tough decision is what led Yogi to perhaps his most Zen-like revelation: "If you come to a fork in the road, take it." Now there's a thought that indicates some serious spatial reasoning capacity.

—Steve Mirsky

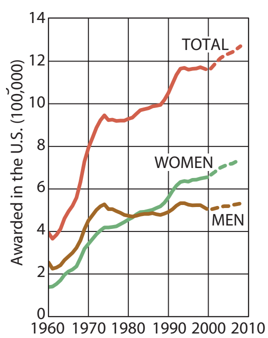
Men, Women and College



RODGER DOYLE

SOURCE: UNESCO, Statistical Yearbook, 1998. Data are for bachelor's or comparable degrees and apply to 1996 except for Bulgaria, Lithuania, Slovenia, Slovakia, Macedonia and Yugoslavia, which are for 1997; Denmark, Finland, Germany, Portugal, Russia, Spain and the U.K., which are for 1995; and Belgium, France, Greece and Switzerland, which are for 1993. Data for Belarus, Hungary, Italy, Latvia, the Netherlands and Ukraine are estimates for the mid-1990s based on enrollment data.

One of the most extraordinary developments over the past two decades has been the growing prevalence of female students on college campuses, particularly in the English-speaking countries and Europe. In the U.S., women became a majority on campuses in 1979 and by 1982 were awarded more bachelor's degrees than men. The number of female graduates, which has been growing steadily for more than a century, is likely to rise further, a trend reinforced in recent years by an unusually large number of women older than 30 seeking higher degrees.



SOURCE: Department of Education. Estimates through 2008.

For reasons not wholly apparent, the number of men receiving bachelor's degrees from U.S. institutions has remained more or less level for the past 25 years. If men had kept pace with women, an additional 1.25 million would have graduated during this time. Perhaps these missing men were high school graduates who, faced with the prospect of delayed earnings and large student loans, went directly to work or to vocational school instead. Perhaps, as Thomas G. Mortenson, editor of the newsletter *Postsecondary Education Opportunity* suggests, the failure of men to keep up with women traces to stresses earlier in life. Boys have had fewer male role models in recent decades because of the decline of two-parent families. Girls in one-parent families ordinarily remain with their mothers and are more likely to find female role models in public schools, where teachers are overwhelmingly female. One result of this disparity, Mortenson says, is that boys are more apt to have poor grades. Eventually the stresses on males, who also suffer disproportionately from learning disabilities, result in lower college enrollment and graduation rates.

American women now receive 55 percent of master's degrees and about four out of 10 of first professional degrees and Ph.D.s; their share of all three types of degrees is rising. In bachelor's and master's degree programs, however, men still predominate in subjects that lead to high-paying jobs. In 1996, for example, women received only 16 percent of bachelor's degrees in engineering and 28 percent in computer and information science. They were overrepresented in subjects that generally lead to lower-paying jobs, such as English (66 percent female) and education (75 percent). In 1998 women aged 25 to 34 with bachelor's degrees working full-time had an average income 22 percent lower than similarly educated men.

In the mid-1990s most countries of Europe and the English-speaking world awarded more bachelor's degrees (or their equivalent) to women than to men, the major exception being Germany. Data for other regions are spotty: among those that awarded a majority of bachelor's degrees to women in the mid-1990s were Brazil, the Philippines and South Africa; Japan, Korea, Iran and Egypt awarded more degrees to men.

The growing educational disparity is most probably affecting the dynamics of mating: in 1970 American women aged 25 to 44 with a bachelor's or higher degree were outnumbered by their male counterparts 58 to 100, but in 1998 they outnumbered males 104 to 100, a ratio that will increase. This difference suggests that educated women will have a harder time finding a comparably educated mate. Women have markedly boosted their share of managerial and professional jobs over the past few decades, a trend that is likely to persist in the next decade. Thus far, more than 11 percent of corporate officers in Fortune 500 companies are women, a proportion that will rise to 17 percent by 2005, according to the New York City–based research organization Catalyst. The National Foundation for Women Business Owners states that the number of people employed by women-owned firms grew from 6.6 million in 1987 to 27.5 million in 1999 and presumably will continue to rise in the next century. *—Rodger Doyle (rdoyle2@aol.com)*

PROFILE

Infamy and Honor at the Atomic Café

Edward Teller has no regrets about his contentious career

As I'm leaving for John F. Kennedy airport, I tell a colleague that I will be away to interview Edward Teller. "Is he still alive?" she asks in amazement. A day later I sit across the room from a 91-year-old man slumped in his desk chair, his five-foot-high carved wooden walking stick leaning against a desk that has a Ronald Reagan–awarded National Medal of Science hanging above it.

With eyes clouded by ulceration, he stares straight ahead. What may have been the world's bushiest eyebrows have thinned. A cowboy boot covers the prosthesis that replaced the foot he lost in a streetcar accident in 1928. His secretary informs me that his memory of recent events has faded in the wake of a stroke. I wonder if he even sees me or whether I will be able to proceed with the interview.

Almost immediately after I sit down, a heavy, slow voice addresses me in a strong, well-enunciated cadence. "I have been controversial in some respects," he announces in an accent that is part European university professor, part cold war inquisitor and part Bela Lugosi. "I want to know what you know about the controversy and what you think about it." I reach for my tape recorder, but he gestures for me to stop. My flustered, inarticulate answer to his first question only evokes another one: "What do you think about Robert Oppenheimer?" he demands, referring to the head scientist of the Manhattan Project whose government security clearance was revoked after Teller testified against him. "There were clearly differences between Oppenheimer and myself. What do you know about this controversy, and what do you think about it?"

TIMOTHY ARCHIBALD

I AM NOT DR. STRANGELOVE, Edward Teller says, defending his hawkish legacy.

Maybe it is payback time for the three articles that *Scientific American* ran in 1950 that voiced strong opposition to the development of the hydrogen bomb, the weapon for which Teller was an unbending advocate when many other atomic scientists were against it. Teller then demands to see what I write before it is published. I refuse. "You realize that I'm now tempted to cancel the interview, and the best I can do is give you an interview with extreme caution, to make sure that nothing is misunderstood."

This nonagenarian whose capacities I had doubted a few minutes earlier has now set me off balance. I've just experienced firsthand the bluster and resolve that prevailed over presidents, generals and members of Congress. Now that he holds the advantage in our encounter, Teller appears ready to submit to questioning.

What follows in the next few hours is like watching an old movie. Many of the lines in the script are familiar, but the effect of their recitation has only grown through repetition. What would have happened, I ask, if we hadn't developed the hydrogen bomb? "You would now interview me in Russian, but more probably you wouldn't interview me at all. And I wouldn't be alive. I would have died in a concentration camp." Commenting on the ban on nuclear weapons tests: "The spirit of no more testing is the spirit of ignorance; I'm happy to violate it. I don't think we're violating it enough."

Teller's persona—the scientist-cum-hawkish politico—is rooted in the upheavals that rocked Europe during the first half of the century, particularly the Communist takeover of Hungary in 1919. "My father was a lawyer; his office was occupied and shut down and occupied by the Reds. But what followed was an anti-Semitic Fascist regime, and I was at least as opposed to the Fascists as I was to the Communists."

To understand Teller, one must remember that he holds a place at the head table of the atomic café: he was present for many of the major events of 20th-century nuclear physics.

He played a bit part in the Manhattan Project's atomic bomb work and became a relentless proponent for and scientific contributor to another weapon that would release unthinkable amounts of energy when atoms fuse together. In 1952 Teller went on to help orchestrate the founding of a second weapons design laboratory, Lawrence Livermore, a competitor to Los Alamos. Livermore succeeded in reducing the size of atomic warheads so that they could fit into nuclear submarines.

Teller conceived a multitude of uses for nuclear explosions, from mining to changing the weather. He campaigned endlessly for nuclear power. He lobbied governor Nelson Rockefeller in the 1960s to undertake programs for the construction of bomb shelters. He was a leading force in convincing presidents Ronald Reagan and George Bush to take on missile defense programs using highly speculative technologies, such as the x-ray laser. More recently Teller has called for nuclear and other explosions to deflect killer asteroids and comets.

What interests me in approaching Teller is trying to understand what he thinks of his own legacy. I ask him what he wishes to be remembered for. “I will tell you in very great detail,” he interjects. “I don’t care.” I wonder whether the father of the hydrogen bomb and the champion of “Star Wars” missile defense has any regrets. “Is there anything that you feel perhaps should not have been done?” I ask. A void of 15 seconds follows. “On the whole, I don’t,” he replies. I inquire whether he still thinks Project Chariot, the never-realized plan to create a new harbor in Alaska by setting off up to six hydrogen bombs, was a good idea. “Look,” he retorts with pedantic emphasis. “With a good harbor, northern Alaska could have been integrated into the American economy more effectively, like Hawaii was.”

Teller is also unrelenting about his contribution to devising the hydrogen bomb. Most accounts credit physicist Stanislaw Ulam with a key insight that made a thermonuclear explosion possible—an idea that came only after Teller had pursued an approach to what was called the “classical Super” that led nowhere. Ulam proposed that the mechanical shock of an atomic bomb could compress hydrogen fuel and unleash a fusion reaction. Teller refined Ulam’s concept by proposing that radiation from the initial atomic blast rather than the mechanical force of the explosion be used to achieve the necessary compression.

So I ask him who can claim paternity for the ultimate weapon of mass destruction, one whose ignition is often referred to as the Ulam-Teller design. As always, Teller does not mince words. “I contributed; Ulam did not,” he says. “I’m sorry I had to answer it in this abrupt way. Ulam was rightly dissatisfied with an old approach. He came to me with a part of an idea which I already had worked out and had difficulty getting people to listen to. He was willing to sign a paper. When it then came to defending that paper and really putting work into it, he refused. He said, ‘I don’t believe in it.’ ” But, I reply, most histories report that Ulam suggested compression as a means to initiate a fusion reaction. “I know, and that is a lie,” Teller shoots back.

Despite this damn-the-world attitude, Teller acknowledges the emotional turmoil he experienced from his outcast status in the scientific community after testifying against Oppenheimer. In 1954 the Atomic Energy Commission was investigating whether Communist sympathies had prompted Oppenheimer to stymie work on the hydrogen bomb. Teller’s action contributed to Oppenheimer’s losing his security clearance and his position as an adviser to the commission. “It hurts badly,” comes the terse reply when he is asked how he feels today about his isolation.


CORBIS/BETTMANN

KILL THE TEST BAN was Teller’s message to a U.S. Senate Committee in 1963.

Nor is Teller fond of the inevitable associations in the public mind with a certain fictional crackpot scientist. “My name is not Strangelove. I don’t know about Strangelove,” he flares. “I’m not interested in Strangelove. What else can I say?” A few moments later, as I pursue the question, he warns: “Look. Say it [Strangelove] three times more, and I throw you out of this office.”

Still, Teller retains an acute awareness of how others see him. After he suffered a stroke three years ago, a nurse quizzed him to probe his lucidity. “Are you the famous Edward Teller?” she queried. “No,” he snapped. “I’m the infamous Edward Teller.”

After my time with him, I walk the streets of Palo Alto and marvel at how this man’s passions have affected anyone who has lived during the past half century. A long-buried memory emerges of my father and grandfather, seated at the dining room table, discussing the materials needed to construct a bomb shelter in our basement that would stop the deadly gamma rays from a nuclear blast hitting New York City, the two men swept into the hysterical maelstrom that Teller helped to fuel. I wonder if Nobelist physicist Isidor I. Rabi wasn’t right when he suggested that “it would have been a better world without Teller.”

As I walk down University Avenue, amid the twentysomethings in cappuccino bars gazing at laptops and perhaps contemplating e-start-up businesses, I realize that the Manichaean world of good versus evil that still kindles Teller’s intensity has faded. His outpost in a modern building at the Hoover Institution, adjacent to the conservative think tank’s phallic stucco tower, sits at the epicenter of the Stanford campus that has served as an incubator of the postnuclear world of the electronics and biotechnology industries. The Soviets could never compete with America’s electronic weaponry—and even less with the northern Californian economic vibrancy that produced Macintosh computers and Pentium processors. Fidel Castro still muses longingly about turning Cuba into a biotechnology powerhouse. In the end, microchips and recombinant DNA—two foundations of the millennial economy—helped to spur the end of the cold war in a way the fantasy of a Star Wars x-ray laser never could.

But Teller is never finished. Even now, at his age, he refuses to put to rest his grandiose visions of technological salvation. He and colleagues have submitted a paper to *Nature* that suggests dispersing sulfur dioxide or other submicron particles in the stratosphere to block sunlight and thus halt global warming—a cheaper option, he claims, than cutting back on carbon dioxide emissions. The man who imitated the sun by harnessing its fusion fires has never yielded his hubristic belief that knowledge of the physical sciences combined with indomitable willpower can fundamentally alter elemental forces of nature and so save the world.

—Gary Stix in Palo Alto, Calif.

TECHNOLOGY AND BUSINESS

FINANCE

DO-IT-YOURSELF FINANCIAL PLANNING

Automated, on-line advice for 401(k)s and other investments takes off

Consider British mathematician Alan Turing's test to see if a computer's responses could pass for human. Then apply it to investment advising. Consumers query both a computer and a stockbroker, using the Internet to avoid prejudicing the results. According to Turing's formulation, if the consumer is unable to distinguish the computer from the broker on the basis of their respective advice, the computer wins. Now consider that the computer-based service costs less than a subscription to the *Wall Street Journal* and is available 24 hours a day, and the computer wins again. At least that's the theory behind the emerging wave of Internet-based services designed to help consumers with their investment decisions. But are consumers ready to accept financial advice from a machine?

Over the past year, more than 10 vendors—including Internet start-ups Financial Engines and DirectAdvice.com as well as major firms such as Standard & Poor's, Intuit (the makers of the popular personal-finance software Quicken and TurboTax) and Fidelity Investments—have introduced on-line financial-advice services. Most are targeted at the 33 million individuals who participate in 401(k) plans and offer specific advice on how to allocate their investments, which now collectively exceed $1 trillion in assets. The number of plan participants expected to use on-line advice is estimated to grow from 1.7 million this year to 13.7 million by 2004, according to the TowerGroup, a market research firm in Needham, Mass. A few other services cater to special situations: for example, RestrictedStock.com, from expert-systems developer MultiLogic, based in St. Paul, Minn., helps individuals determine when to sell heavily regulated restricted stock, such as shares acquired in private sales, mergers or via stock options.

"There's no question that people are going to think very differently about their finances as advice moves from analog to digital-based systems," says Paul G. Koontz, a general partner at Foundation Capital, which has invested $7 million in Palo Alto, Calif.–based Financial Engines. "Today advice is based on human judgment and relationships. In five years, investment decisions will be made with science."

Founded by Stanford University emeritus professor William F. Sharpe, Financial Engines is a notable example of applying scientific methods to the task of investment decisions. Sharpe was awarded the 1990 Nobel Prize in Economics for his work on the capital-asset pricing model—the $E = mc^2$ of modern portfolio theory, quantifying the relation between risk and return of financial securities. With Financial Engines, he hopes to provide individual investors with the same sophisticated analysis tools used by pension-fund managers. The company launched its $60-a-year, consumer-advice service in June.

Similar to large-scale weather forecasting or aerodynamic testing, Financial Engines employs simulation models to forecast how a 401(k) portfolio is likely to perform under possible combinations of interest, equity returns and inflation. The models are fed by a database of past returns of more than 15,500 securities. The software runs the users' current investments through thousands of economic scenarios and calculates the probability that the portfolio will meet their retirement goals. The software then constructs an optimal portfolio that maximizes the expected return for a given amount of risk.

COURTESY OF FINANCIAL ENGINES, INC.

ECONOMIC SCENARIOS by Financial Engines's software uses models akin to those used in weather forecasting to help individuals plan for their retirement.

Institutional money managers routinely use such analytical modeling software. Experts readily admit, however, that there is no conclusive way of measuring the quality of investment advice, whether human or computer-generated, without conducting long-term statistical studies.

The measurements are further complicated by the fact that sound advice does not always lead to favorable outcomes because of underlying uncertainties in the market. "You need a lot of data to know if someone is smart or lucky," explains Christopher L. Jones, Financial Engines's vice president of financial research and strategy. "In most cases, it doesn't exist." He recommends that investors stick with methodologies that seem prudent, well informed and free from conflicts of interest but acknowledges that, in the end, selecting an adviser "comes down to trust."

Others, such as Daniel O. Leemon, executive vice president of business strategy at Charles Schwab, contend that there is more to providing investment advice than simply offering trusted analytics: "Most investors still need the psychological comfort and reassurance that a human adviser brings." Leemon thinks it may be some time before consumers are confident enough to rely on Web-based advice systems. "The traditional brokerage industry has made people insecure about their finances. As a result, most people are uncomfortable about making these decisions without help."

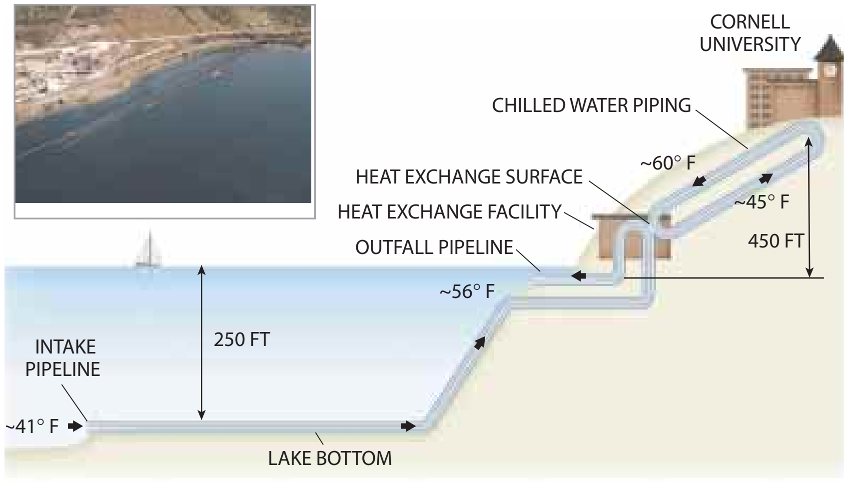
James P. Punishill, an analyst at Cambridge, Mass.–based Forrester Research, a market consulting firm, suspects that the problem runs even deeper. "All of our surveys have shown that most people have co-dependent relationships with their brokers," he says. "They want someone to blame."—*Michael Menduno*

MICHAEL MENDUNO (www.menduno.com), based in Santa Cruz, Calif., holds master's degrees in mathematics and in engineering-economic systems from Stanford University.

CIVIL ENGINEERING

IN THE DRINK

Cities try cooling off with deep lake water



JON REIS *Photolink* (*photograph*); LAURIE GRACE (*illustration*)

COOLING CORNELL: cold water from Cayuga Lake will be drawn up in pipes, some of which have been laid* (photograph), *to air condition Cornell University.

Even on a muggy, 90-degree July day in Ithaca, N.Y., the depths of nearby Cayuga Lake are a nippy 40 degrees. This simple fact has pointed Cornell University, the town's largest economic entity, toward a novel solution to its energy demands for cooling. The university has embarked on a $55-million project called Lake Source Cooling, which by mid-2000 will be using cold water from the lake to reduce Cornell's energy consumption for air conditioning by 80 percent.

To make this happen, the university is laying underground a huge pipeline in two distinct segments. One segment, 1.6 meters (5.25 feet) in diameter, will draw water from Cayuga (the longest of the Finger Lakes) from a depth of 76 meters, raise it to a heat-exchange facility on shore and then discharge it into a shallower part of the lake. A separate line of somewhat smaller underground pipes will carry water downhill from Cornell, about three kilometers (two miles) away, to the heat exchanger and back up again. The Cornell water and the lake water will never mix, but heat will be transferred through stainless-steel plates.

It's a big undertaking, but something has to be done, the university says. Its present chilled-water system relies heavily on ozone-depleting chlorofluorocarbons, whose manufacture was banned in 1996. Less harmful refrigerants are now available, but deep-water cooling is expected to be more economical in the long run, although the break-even point may be 30 years away. And because less coal will be burned to produce electricity, the project will reduce Cornell's contribution to global warming.

Cornell isn't alone in pursuing this approach. Toronto District Heating Corporation has tunneled under downtown, laid pipes and is signing up customers for a system that will use water from Lake Ontario. But the intake line won't be laid until enough customers are on board, according to Steve Zucchet of Toronto District Heating. He estimates that the system will be operating by 2001 or 2002.

So far, though, only a few other locations are using deep-water cooling systems. Stockholm has had one since 1995, using seawater from the Baltic. Smaller projects are located in Halifax, Nova Scotia, and Keahole Point, Hawaii. Webster, N.Y., near Rochester, also has designs on Lake Ontario's chilling power.

Given the basic simplicity of the concept, its cost-effectiveness and the environmental benefits, is deep-water cooling the wave of the future? "The short answer is no," Zucchet says. Few cities have Toronto's "high air-conditioning load so near to deep water." Pumping large volumes of water long distances is expensive, he points out, noting that his farthest customer is only one kilometer from the heat exchanger.

At Hawaii-based Makai Ocean Engineering, which designed the pipelines at Ithaca and Keahole Point, president Joseph Van Ryzin agrees that few cities "meet the magic formula." Those that do sometimes face obstacles that have nothing to do with geography.

Look at Guam, Van Ryzin says. "A bay lined with hotels, miserable high humidity all year, excellent access to deep water, high electrical costs, a power company famous mostly for its brownouts. Technically, environmentally, economically, it is a slam-dunk." Yet deep-water cooling isn't happening. The problem in Guam and elsewhere, he suggests, is politics and community squabbling. Toronto, he notes, has been discussing deep-water cooling for 20 years.

In Ithaca, Cornell's path has not been entirely smooth, in part because of the emotional responses such a monolithic institution can stir up in a small town: opposition bumper stickers read "It's OUR lake, not Cornell's." Ithaca is the only site where a deep-water cooling project has provoked significant, though not widespread, protest—most of it, ironically, on environmental grounds. The fear is that the temperature of the discharged water (48 to 56 degrees F) as well as its phosphorus content will encourage algal blooms and weed growth.

Those problems are misconceptions, according to Ithaca College biologist John L. Confer, who says the added heat amounts to no more than an extra hour of summer sunshine and that the discharge will actually contain *less* phosphorus than the receiving waters. The most important aspect of the project, Confer wrote in the *Ithaca Journal,* "is that it would set a national example for reducing global warming."

Most Ithaca-area ecologists apparently agree. Nevertheless, an ad hoc group filed suit to stop the project. The suit has been dismissed twice, but the plaintiffs are pursuing their last resort, a hearing in the New York State Court of Appeals. With a decision likely in late September, Cornell still hopes to have the shell of the building up and the intake line anchored in the chilly depths of Cayuga before winter sets in. *—Liz Holmes*

LIZ HOLMES, based in Ithaca, N.Y., is author of a book of poetry, The Patience of the Cloud Photographer *(Carnegie Mellon, 1997).*

PLANT SCIENCE

TO BOLDLY GROW...

A new technique for altering genes could bring improved crops

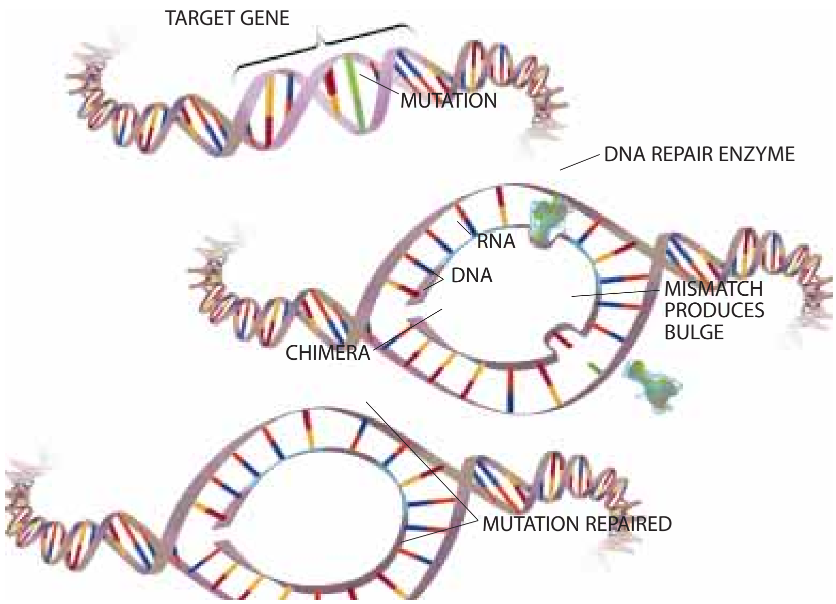
One of the most useful tricks in a geneticist's toolkit is called gene targeting. It allows researchers to alter specific genes in cells by adding or cutting out fragments of DNA. But standard gene targeting is laborious and inefficient—thousands of cells have to be treated to modify just a few of them. And, to the chagrin of seed companies that would like to use gene targeting to improve crops, it does not work well with plant cells.

Now plant scientists are reporting remarkable success in adapting a controversial new technique previously used to modify genes in animal cells. The technique is known as chimeraplasty, because it is based on molecules that are hybrids, or chimeras, of DNA and its chemical relative, RNA. Several peer-reviewed papers have described how chimeraplasty, invented by Eric B. Kmiec of Thomas Jefferson University, can efficiently modify genes in mammalian cells—but results are variable and inconsistent. Mario R. Capecchi, the University of Utah scientist who invented standard gene targeting, is unconvinced that chimeraplasty modifies genes in mammalian cells in the way that Kmiec and his associates suggest. But Capecchi allows that plants may be different.

Kmiec hit on the idea of chimeraplasty a few years ago. While investigating simple molecules that would alter DNA in controllable ways, Kmiec became convinced that RNA and DNA sometimes bind to each other more strongly than the two strands in a DNA double helix bind to each other. He designed a chimeric molecule to exploit the effect: an almost closed loop made mainly of DNA but including two stretches of RNA. Between the two RNA regions is a very short stretch of DNA that serves as a template.

According to Kmiec, when the chimeric molecule is introduced into cells, the RNA sequences find and glom onto a target gene, by binding tightly to corresponding sequences in the gene's DNA. The bound RNA sequences thus hold the template DNA between them adjacent to the gene. The template's sequence is similar to the gene's at that point, but not identical. Then the magic happens. In some cells the target gene sequence changes to resemble the template's sequence. Kmiec thinks DNA-repair mechanisms in the cell erroneously copy the DNA template. The hybrid molecule soon degrades.

In 1994 investors set up a company, Kimeragen in Newtown, Pa., to devise medical therapies based on Kmiec's molecules, and it is now planning to launch the first clinical trial of a gene-repair



***MUTATED GENE** can be repaired with a chimeric molecule consisting of DNA and RNA. Enzymes modify the gene to match the chimera, which later degrades.*

therapy for a rare inherited condition, Crigler-Najjar disease. Experiments with plants started after Charles J. Arntzen of the Boyce Thompson Institute for Plant Research at Cornell University heard about the technique and received a grant from Kimeragen. He says his first experiment worked the first time—an almost unheard-of event in biotechnology.

Pioneer Hi-Bred International, a large seed company that is looking for ways to modify genes in its products, soon joined the party. This past July Ben Bowen and other Pioneer researchers published in the *Proceedings of the National Academy of Sciences USA* details of how they used Kmiec's method to make corn plants resistant to two common herbicides and prompt them to repair an inactive gene for a fluorescent marker protein. The repair was passed on to the plant's progeny. The workers used a gene gun to fire microscopic particles of gold coated with the chimeric molecules into plant cells.

A paper published alongside Bowen's describes how Arntzen and others at the Boyce Thompson Institute used chimeraplasty to modify tobacco plants, also making them resistant to an herbicide and correcting a mutation in a marker gene. The efficiencies reported in the two papers are not as high as in some chimeraplasty experiments with mammalian cells. But the results suggest the technique could be a boon for plant science.

Arntzen points out that the commercial crop breeders have been introducing mutations into crops from closely related species for some years. The new technique means researchers should be able to duplicate in a crop any mutation found to be beneficial in any studied species—without having to transfer a whole gene. He predicts seed companies will within a few years be selling crops that have been genetically modified specifically to improve how they respond to food processing. And he speculates that some opponents of gene splicing in crops may find gene modification less worrisome, because the technique does not involve transferring whole genes.

That may be a cynical hope. Furthermore, chimeraplasty seems capable of bringing about only small physical changes in a gene. But small changes can have big effects: Anthony J. Cavalieri of Pioneer says the company is already trying chimeraplasty with genes that would boost the oil content of seeds. Products could arrive in five years, he estimates.

—Tim Beardsley in Washington, D.C.

CYBER VIEW

To Err Is Mechanical

Moore's Law, the observation that computers' speed and memory capacity double about every 18 months, means that today's mass-market PC can run rings around the past decade's high-end mainframe. Unless you really insist on having the right answers. One unfortunate corollary of Moore's Law is that reliability levels that were perfectly adequate for machines performing a measly few million operations per second may fall short as computer clock rates head for one gigahertz or more. Odds of a billion to one against errors sound fine until you do the math.

Most digital devices today have even lower error rates—hard-disk drives miss only one bit per 10 trillion or 100 trillion bits per read and the lowly CD-ROM one in a trillion. For a high-speed drive that can transfer 300 million bits a second, that's a mistake every few days of nonstop production. And for a full CD-ROM, that's one undetected error in every 200 software installations. But a few years ago, when desktop disks topped out at 40 million bits a second, you could expect undetected errors about once a month of continuous use.

Word processors and spreadsheets generally wrote information to disk only a few times a minute, in chunks of perhaps a million bits, so that error rate translated to several years of actual operation. Faster disks, however, have encouraged more intensive use—a multimedia stream of video and audio might demand tens of millions of bits per second for minutes or hours at a time. Furthermore, thanks to modern compression techniques, a single erroneous bit can corrupt the information contained in millions of subsequent ones.

Misread bits in a data file could be relatively innocuous (unless the erroneous data were saved back to disk), but those within a program or operating-system software could cause dangerous crashes. And undetected errors in a disk's directory could render all its information inaccessible.

As the amount of information stored on disks increases, of course, the chances for error increase proportionally. IBM's new 25-gigabyte disk for laptops can store the equivalent of about four feature films. Expect one undetected error per 50 digital perusals of the entire disk. At 750 gigabytes (perhaps five years away with current disk-drive trends), today's error rates would call into question the ability to write and read a disk consistently even once—as would be needed, for example, to format its tracks and sectors for use.

Engineers already know how to get around this kind of problem—they've been doing it for decades on mainframes and database servers through checksums and error-correcting encodings. Checksums, which distill a "signature" of a file into a few bytes, can determine whether any information has been damaged. Error-correcting codes, which add extra bits to each byte of data, can recover the original even if 10 percent or more of it has been corrupted. Together, and on top of the error correction already performed by the disk's hardware, they can improve the integrity of data by a factor of one billion or more. Such safety precautions have generally been considered too expensive and finicky for personal computers, but as the price of memory falls and the cost of failures rises, that cost-benefit calculation may change.

Indeed, Apple Computer is reportedly considering error-correcting memory for future generations of its computers—although any given RAM bit is expected to flip once in many billions of hours of operation (usually thanks to a passing cosmic ray), growing RAM consumption makes even small numbers significant. Statistics from Micron Technology, for example, suggest that a computer with 16 megabytes of RAM will experience a failure perhaps once every 15 years, but many computers now hold 128 megabytes or more, yielding an expectation of memory errors a little more often than once every two years for chips in perfect operating condition. (For a large company with a network of 10,000 PCs, that means about a dozen memory errors on any given day.) The cosmic-ray connection means that RAM error rates vary sharply with altitude: computers in Denver will experience flipped bits at several times the rate for those in San Francisco, and airborne travelers may experience more than 20 times as many errors as their ground-based colleagues.

DAVID SUTER

As Micron and others point out, extirpating memory and disk errors simply makes other possibilities for data corruption more visible. The specifications for a typical computer's buses and cables do not rule out data loss, and even the central processing unit is not immune to errant cosmic rays. Instead of trying to stamp out errors, some computer systems just work around them. Consider the Internet: a T1 line, the archetypal high-speed digital link, has a specified error rate of a mere one in a million bits. That's an error and a half every second on a single link, perhaps tens of thousands per second Internet-wide when everything is working as planned. But every packet that travels down the T1 has a checksum that lets only one out of every 65,536 corrupted packets pass unnoticed. That's about one error every 12 hours. In addition, a separate checksum verifies the data at the far end of its journey, perhaps a dozen or more hops away. And when a system connected to the Internet detects a corrupted or missing packet—some nodes can drop 30 percent or more of their traffic on a bad day—it uses a carefully specified protocol to request a new copy of the missing bits and insert them in their proper place.

It may seem odd that the computers on desktops or in toasters will eventually use techniques developed for megacompanies and strategic military operations. But then again, a single individual appropriately equipped today may well control more computing power than did the entire U.S. air-traffic-control system 15 years ago. As hardware reliability catches up to increased computing power, perhaps operating systems that don't crash every few days or weeks won't be too far behind. *—Paul Wallich*

The Hidden Ocean of

Doodles and freckles, creamy plains
and crypto-icebergs—the amazing surface
of Jupiter's brightest icy moon
hints at a global sea underneath

by Robert T. Pappalardo, James W. Head and Ronald Greeley

EUROPA'S ICY COUNTENANCE resembles a cracked eggshell. Reddish material has oozed out of fractures opened up by Jupiter's gravitational forces. Very few craters are present, indicating that the surface is geologically young. On this Galileo spacecraft image, the colors are exaggerated but real. Other spacecraft instruments have found that Europa's interior is mainly rock, with an outer layer of water (in either liquid or solid form) about 100 kilometers thick (*bottom right*). Most of that water must be fluid or semifluid to account for surface features, such as the circular mounds pushed up by rising blobs of relatively hot ice (*far right*), which occasionally puncture the surface.

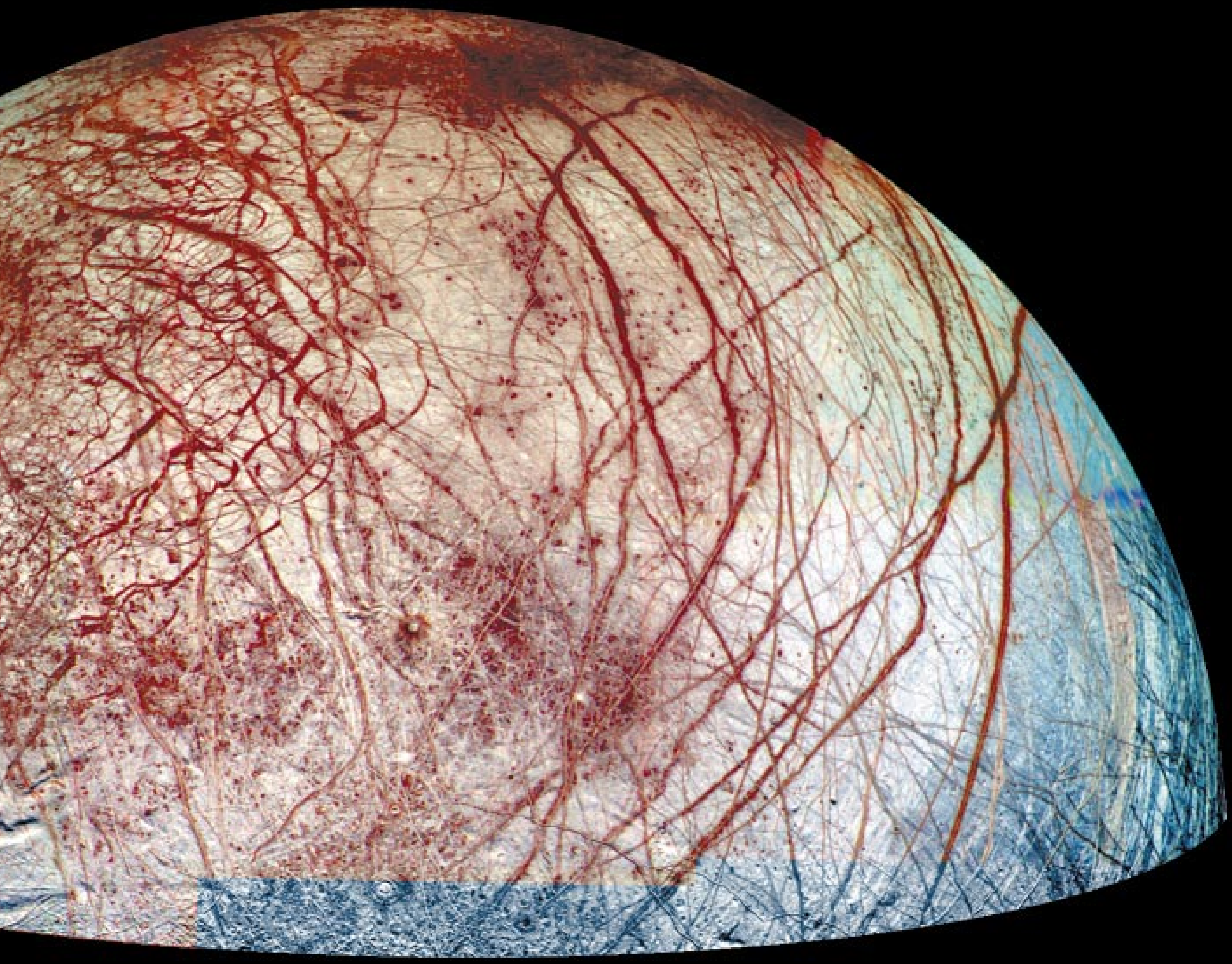
Do living things flourish elsewhere within our solar system, or is Earth's environment uniquely nurturing? This question is central to planetary exploration today. Three decades into humankind's reconnaissance of the planets and their natural satellites, only a short list of possible abodes remains. Perhaps the most intriguing is Jupiter's ice-rich moon Europa.

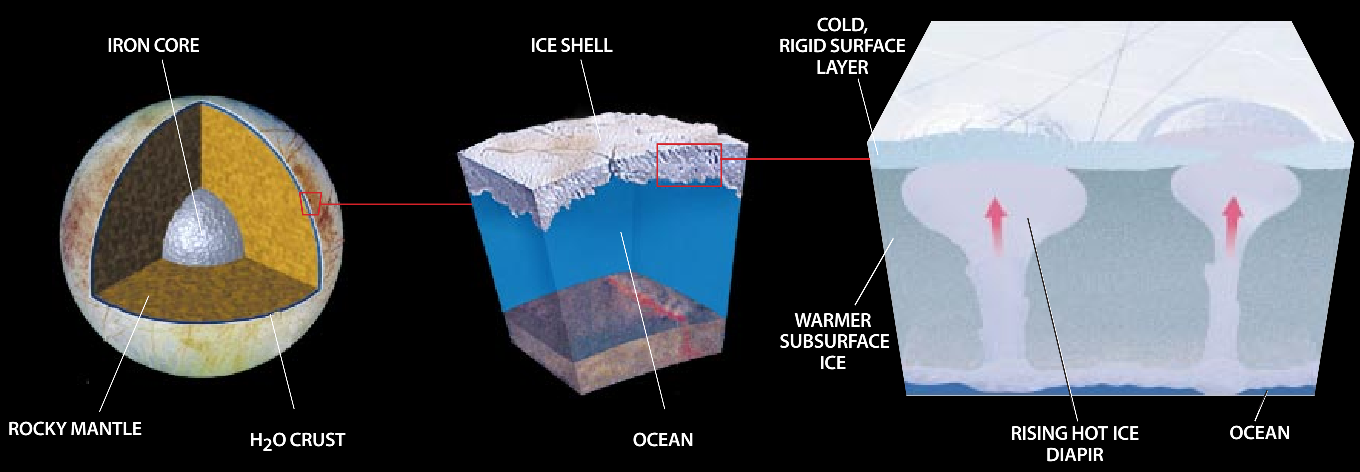
For centuries, astronomers knew Europa only as a pinprick of light in even the most powerful telescopes. In the 1960s spectroscopy showed that the satellite, like many others in the cold reaches of the outer solar system, is covered with ice. With surface temperatures of 110 kelvins (–260 degrees Fahrenheit) near the equator and 50 kelvins near the poles, that ice must form a rock-hard skin. Researchers had no way to probe deeper and little reason to expect anything special. But in the past two decades and especially in the past few years, spectacular images radioed from visiting spacecraft have revealed a young and tremendously deformed surface. Somewhere under the icy shell, it seems, must be a warm, mobile interior. Is it glacial ice? Or are Europa's innards warm enough to sustain an ocean of liquid water? If the latter, we can stretch our imaginations and ask whether life might have arisen within the lightless depths.

Planetary scientists have been trying to infer what lies inside Europa ever since the two Voyager spacecraft flew by Jupiter and its companions in 1979 [see "The Galilean Moons of Jupiter," by Laurence A. Soderblom; Scientific American, January 1980]. Celestial mechanics dictated that these spacecraft could pass by Europa only distantly. The photographs they did obtain were nonetheless tantalizing. Europa looked like a ball of string, its bright plains crisscrossed with bands and ridges. Researchers noticed that some dark wedge-shaped bands have opposing sides that match each other perfectly. Somehow the bright icy surface has been wrenched apart, exposing dark material that was fluid enough to permeate the ensuing void. These features resemble liquid-filled openings between floating plates of sea ice on Earth.

Unexpectedly, the Voyagers found very few large impact craters on Europa. A planetary surface slowly accumulates impact craters as it is occasionally hit by cometary and asteroidal debris. If Europa all but lacks visible craters, it must have been repaved by volcanic or tectonic events in the relatively recent past. Based on the number of comets with Jupiter-crossing orbits, the late cratering expert Eugene Shoemaker deduced that a crater larger than 10 kilometers (six miles) in diameter should form

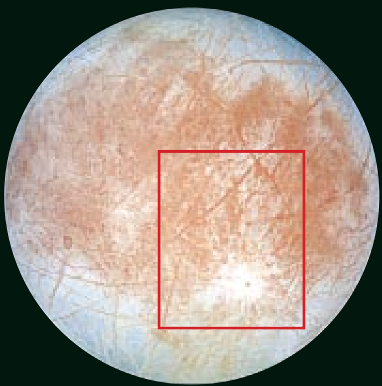
Europa

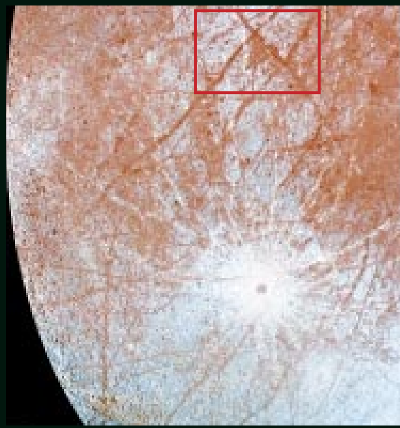


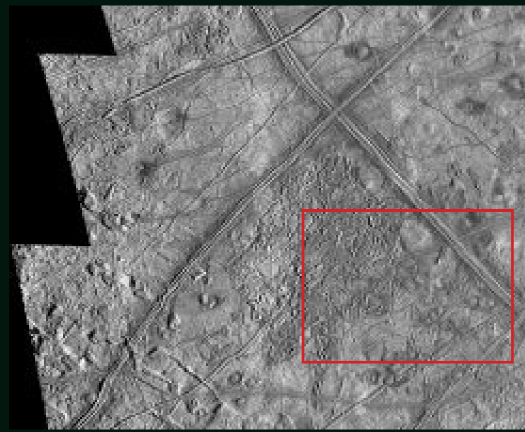


NASA/JET PROPULSION LABORATORY; CYNTHIA PHILLIPS AND MOSES MILAZZO *University of Arizona* (*top*); NASA (*left and center*); TOM MOORE (*right*)

Soft Landing on Europa







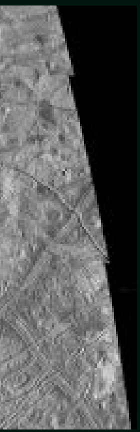
NASA/JET PROPULSION LABORATORY; ALFRED T. KAMAJIAN (*bottom left*)

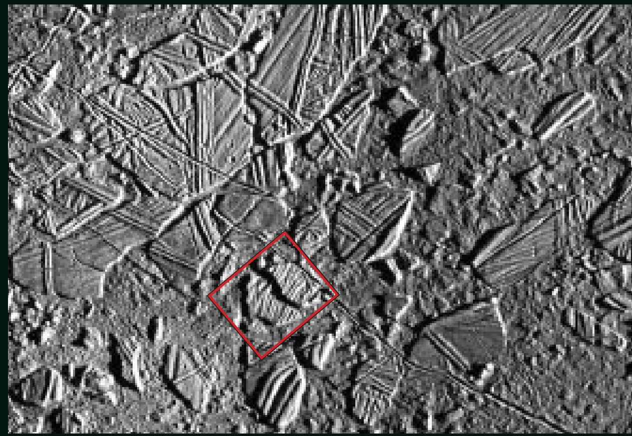
once every 1.5 million years on average. Extrapolation from the few known Europan craters suggested that 45 of this size might exist across the satellite, indicating a surface age of just 30 million years—a geological eyeblink. Shoemaker added that Europa's large craters might have flattened out over time if the interior were warm. The satellite could be active even today.

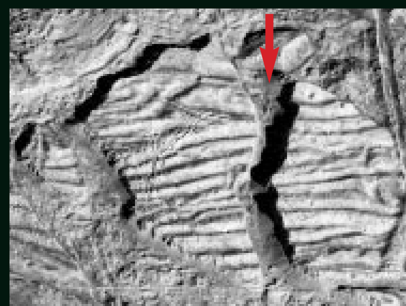
But this hypothesis remained uncertain. The Voyager images were too coarse to pick out smaller craters. Indeed, intermingled with the bright plains is mottled terrain filled with dark spots, mounds and pits. Some researchers pointed out that craters could be hiding in these odd regions, in which case the satellite's surface would be ancient. Besides, how could a moon so small possibly be active? Similarly sized bodies, such as Earth's moon, are inert balls of rock, having lost most of their internal radioactively generated heat long ago. By all rights, Europa should now be cold and dead.

The Paper Clip Moons

Then researchers came to appreciate the power of an exotic heat source: tidal kneading, the process that drives volcanism on Europa's pizza-colored neighbor Io. Of the four large moons of Jupiter—Io, Europa, Ganymede and Callisto, collectively known as the Galilean satellites in honor of their







Simulated view of icy blocks, roughly three kilometers from side to side

GIANT BLOCKS OF ICE the size of a small city are progressively revealed in this sequence of Galileo images. A colossal X formed by two ridges (*first three images in top row*) helpfully marks the spot as the pictures zoom in on a dark splotch known as Conamara Chaos (*next two images*) and thence to individual iceberg-like blocks (*above*). Warm ice, slush or liquid water once filled the low-lying "sea" in which the blocks sit, now frozen in place. An artist's impression (*left*), simulating a vantage point a few hundred meters above the surface looking south (*arrow in above image*), shows dirt tumbling downslope as fine ice particles slowly evaporate away.

discoverer—the first three are engaged in an elegant orbital dance called the Laplace resonance. With clockwork precision, each time Ganymede orbits Jupiter once (with a period of 7.2 Earth days), Europa orbits twice (3.6 days) and Io four times (1.8 days). The consequent gravitational push and pull distorts their orbits into oblong ellipses. They move nearer to, then farther from, their parent planet during each orbital revolution. In response, tides are raised and lowered in the body of each satellite. Like bending a paper clip rapidly back and forth, this tidal flexing generates heat [*see bottom illustration on page 61*].

The effects are felt most profoundly on Io, which is the closest to Jupiter. The interior temperature rises to the melting point of rock, powering continual volcanic eruptions. Europa, farther away, is heated less intensely. But the latest calculations indicate that its interior might be kept warm enough to melt ice below a depth of 10 to 30 kilometers, maintaining a global subsurface ocean.

After Voyager, observational tests of the ocean hypothesis had to wait nearly 20 years, until the worlds of Galileo could be visited by the spacecraft named for him. That spacecraft swung into orbit around Jupiter in December 1995. Every few months since then, its trajectory has brought it speeding closely past one of the Galilean satellites—including, a dozen times, Europa.

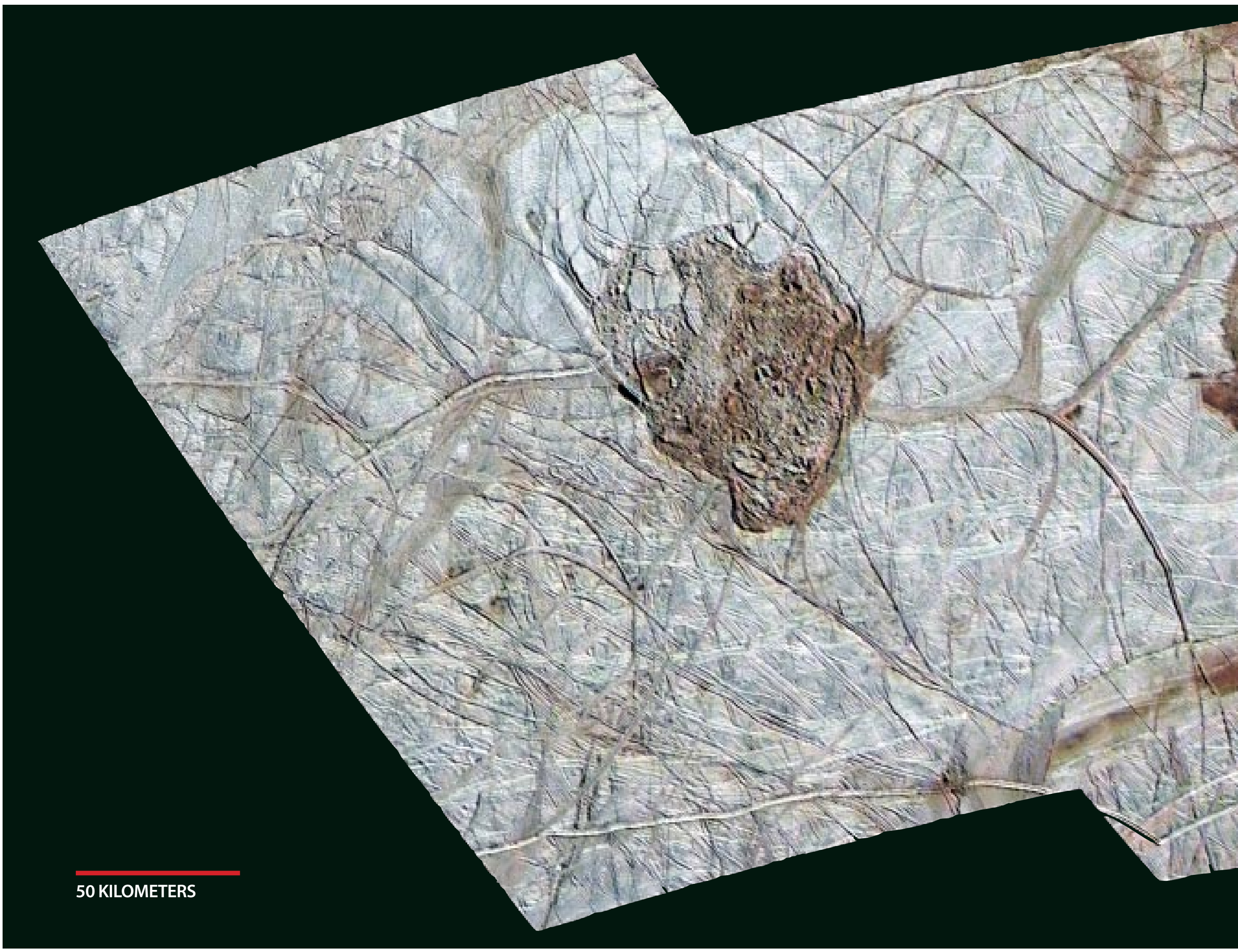
Even if Galileo had not sent back a single picture, it would have provided a vital insight. On each flyby, engineers and scientists have carefully tracked the spacecraft's radio signal in order to measure Europa's gravitational field. Any rotating and tidally distorted moon is slightly flattened, or oblate, so its gravitational field is also nonspherical. The irregular force causes slight shifts in the frequency of Galileo's signal, from which researchers have quantified the satellite's oblateness and, in turn, its internal mass distribution. (For a given rotation rate, a satellite with a more centrally concentrated mass will be less oblate than a homogeneous satellite.)

Tapestries and Hydraulic Bearings

Judging from its average density of 3.04 grams per cubic centimeter, Europa is predominantly a rocky object. The gravity data indicated that the rock is sandwiched between a central iron core and an outer crust of H_2O. Considering the likely range in density values for the iron core and rocky mantle, the water crust is between 80 and 170 kilometers thick, most likely about 100 kilometers. If a significant portion of it is liquid, its volume exceeds that of all the oceans of Earth combined. But Galileo's gravity data cannot tell whether this water layer is completely solid or partially liquid.

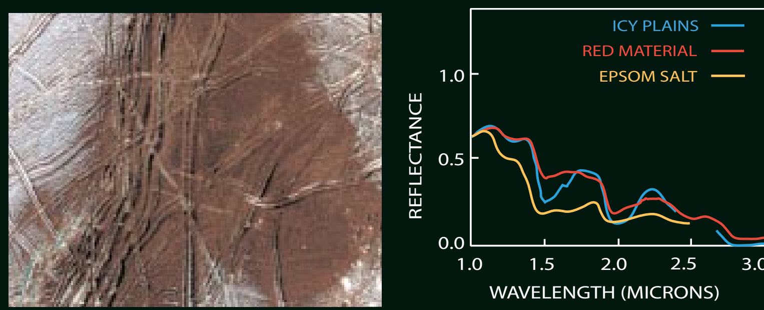
To address that question, one must look at the pictures. The Galileo imaging team found a world like no other. Its surface is an elaborate weave of fractures, ridges, bands and spots. The fractures presumably formed as tidal forces distorted the icy surface until it cracked. Ridges are similarly ubiquitous. They slice across the surface in pairs, each with a narrow valley down the center. Plausible models for their formation invoke the rise of liquid water or warm glacial ice along fractures. A watery or icy "magma" might have forced the rigid near-surface ice upward, warping it into a double ridge. Or an icy slurry might have erupted onto the surface to build each ridge. Multiple parallel ridges also occur, indicating that the process can repeat to create ridges side by side. The widest ones are commonly flanked by dark, reddish, diffuse-edged stripes. Perhaps the heat pulse associated with ridge formation created these darkened margins through icy volcanism or sublimation of a dirty ice surface. Whatever their exact formation mechanism, ridges point to a dynamic geological history and warm subsurface.

From the seemingly random doodlings of fractures and ridges, scientists have attempted to understand the manner in which Europa has been stretched and distorted. Tidal kneading produces a distinctive pattern, and some of Europa's freshest cracks and ridges fit that pattern. But something else must also have been going on. Strangely, it appears that the stress pattern has swept across the surface over time.



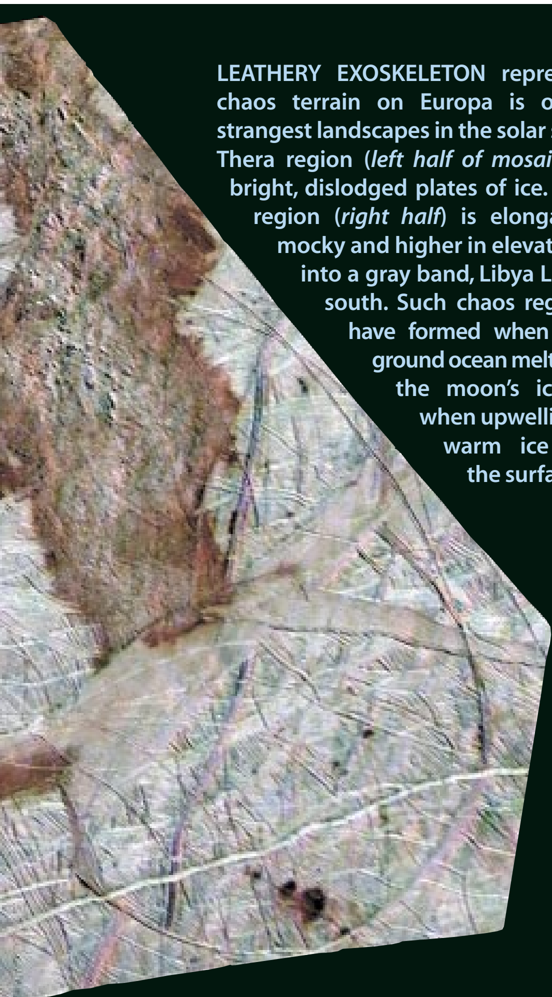
In fact, the pattern can be explained if Europa's surface has rotated faster than its interior. Most of the solar system's natural satellites are in synchronous rotation: torqued by tidal forces, they come to rotate exactly once for each orbital revolution, always showing the same face to their parent planet. (This is why we always see the same side of our moon from Earth and so speak of the moon's "far" side.) But if Europa's icy surface were decoupled—mechanically separated—from its rocky mantle, Jupiter's gravity would cause the surface to spin slightly faster than the synchronous rate. A subsurface ocean could easily act as such a bearing, allowing the floating ice shell to rotate nonsynchronously.

It cannot be said with certainty whether nonsynchronous rotation is going on today or whether the surface instead records an ancient pattern of now inactive lineaments. Scientists have compared the locations of features in Galileo images to their locations in Voyager images and found no measurable change over that 20-year period. Relative to the interior, the surface today cannot be rotating faster than once every 10,000 years.



RUDDY SPOT marks where briny liquid poured out onto Europa's surface (*left*). Spectral measurements (*right*) found that surrounding bright plains (*blue*) consist mainly of water ice. The ruddy material (*red*) more nearly matches the laboratory spectrum of magnesium sulfate (*yellow*).

NASA/JET PROPULSION LABORATORY (*left*); SARAH DONELSON; SOURCE: THOMAS B. McCORD *University of Hawaii* (*right*)



LEATHERY EXOSKELETON represented by chaos terrain on Europa is one of the strangest landscapes in the solar system. The Thera region (*left half of mosaic*) contains bright, dislodged plates of ice. The Thrace region (*right half*) is elongated, hummocky and higher in elevation. It spills into a gray band, Libya Linea, to the south. Such chaos regions might have formed when an underground ocean melted through the moon's icy shell or when upwelling blobs of warm ice disrupted the surface.

NASA/JET PROPULSION LABORATORY; CYNTHIA PHILLIPS *University of Arizona*

Galileo's camera has also homed in on the dark wedge-shaped bands, where low-resolution Voyager images hinted that the ridged plains have pulled completely apart. Recent analyses have confirmed that the opposing sides of these bands are perfectly matched. The dark material in between is finely striated, commonly having a prominent central groove and some degree of symmetry [*see illustration on next page*]. These bands may be the icy equivalents of spreading centers—locations on Earth's ocean floors where tectonic plates move apart and new rock surges up. If so, the subsurface ice must have been mobile and warm at the time the features formed. But plate tectonics is a zero-sum game: if some material emerges from the interior, other material must descend. On Earth this descent occurs at subduction zones. No such zones have yet been identified on Europa.

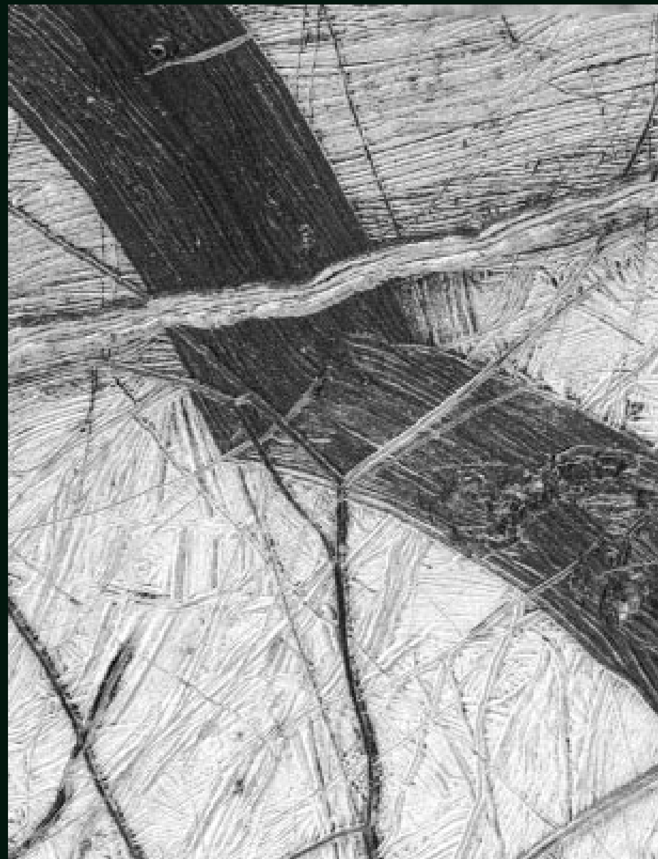
Blame the Blobs

The mysterious mottled terrain provides further clues to Europa's interior. Galileo's images of this terrain are 10 to 100 times more detailed than Voyager's. They show it to be peppered with circular and elliptical features that the imaging team named lenticulae, Latin for "freckles." Many are domes, some are pits and some are smooth dark spots; others have a jumbled and rough texture. The dome tops look like pieces of the older ridged plains, intimating that the domes formed when the plains were pushed upward from below.

The variety of lenticulae can be explained if Europa's icy shell has behaved like a planetary lava lamp, with blobs of warm ice rising up through the colder near-surface ice. In that case, domes formed when the blobs pressed against the underside of the surface. Rough textures may be places where blobs disrupted and destroyed the plains. Smooth dark patches may be meltwater unleashed by blobs and quickly refrozen.

Blobs—technically, diapirs—would naturally develop if Europa's icy shell floated above liquid water. In this scenario, tidal flexing pumps heat into the base of the shell, where ice is near its melting temperature and most easily deformed. The warm ice is less dense than the cold ice above, so it attempts to rise. If the ice shell is thick enough, buoyancy forces can overcome the viscous resistance to flow (which lessens with depth). Like wax rising in a lava lamp, warm-ice diapirs will rise toward the surface, where they could create the visible lenticulae. Models suggest that the shell would have to be at least 10 kilometers thick.

As well as the lenticulae, mottled terrain contains the most



CRACKS IN THE ICE on Earth (*left*) and Europa (*right*) bear a superficial resemblance. In terrestrial polar seas, floating ice breaks apart to expose darker liquid water, which quickly freezes. The cracks can slam closed to push up ridges. On Europa, however, the dark bands and paired ridges are thought to result from tectonic processes. The scale is vastly different: this break in the sea ice is 100 meters wide, whereas the dark band on Europa is more than 15 kilometers wide.

MAX COON *Northwest Research Associates (left)*; NASA/JET PROPULSION LABORATORY; ROLAND WAGNER *German Aerospace Research Agency (right)*

spectacular of Europa's features: regions of "chaos." In these jumbled areas, small icy remnants of preexisting ridged plains appear to have jostled in a hummocky matrix—like icebergs calved into a slushy sea. The original arrangement of the iceberglike blocks can be reconstructed like a jigsaw puzzle, and researchers have done so for one of these areas, Conamara Chaos [*see illustration on page 63*]. If the regions formed when subsurface water melted through Europa's icy shell and then refroze, the iceberg analogy may be right on target. Another possibility is that one or more diapirs welled up and heated the near-surface ice, creating a slushy bed of ice and liquid on which the cracked and dislodged blocks of ice could slide freely. Either way, the chaos regions tell of a warm subsurface and at least partial melting.

The one type of feature the mottled terrain conspicuously lacks is small impact craters. So the surface of Europa must indeed be young. Following on Shoemaker's pioneering age estimates, researchers have modeled the solar system's comets and asteroids to understand the rate at which they impact Europa. They agree with Shoemaker's suggestion that it is primarily comets that slam into the Galilean satellites; asteroids are simply too few in number. From the presumed and observed numbers of comets in the vicinity of Jupiter—including Comet Shoemaker-Levy 9, which plunged into the gas giant in July 1994—scientists calculate that the sparsely cratered landscape of Europa is 10 million to 250 million years old. By geological standards, that is a short amount of time. Therefore, it seems likely that Europa is still active today, although no volcanic smoking guns have been found, as on Io.

The few craters that do exist on Europa's surface are themselves a probe of the thickness of the icy shell. Unlike the bowl-shaped or flat-floored impact craters on other worlds, Europa's two largest impact features have a central smooth patch surrounded by concentric rings [*see top illustration on opposite page*]. The blasts that created these features must have penetrated the rigid near-surface ice to a weak layer below. Because the weak layer was unable to maintain a crater shape, melt and slush quickly filled in, dragging the near-surface ice inward and fracturing the surface in concentric rings. In essence, the rings are the frozen record of a rock thrown into a pond—a very big rock and a very big pond. Scientists have estimated the dimensions of the original impact from the visible scars; in turn, the depth to the weak layer is six to 15 kilometers, in rough agreement with values from the tidal-heating theory and the blob models. But some regions of Europa's ice shell might be significantly thinner than others, a point researchers continue to debate.

The Bands of NIMS

In addition to its camera, the Galileo spacecraft carries a near-infrared mapping spectrometer (the NIMS instrument), which has analyzed the light reflected by Europa's surface. As expected, NIMS found the characteristic spectral bands of water ice. Yet the bands are skewed and asymmetric in shape, a sign that some impurity is mixed into the ice, especially in areas that appear dark and reddish at visible wavelengths. A prime suspect is a salt—specifically, magnesium sulfate [*see top illustration on previous page*]. If so, sitting on Europa are the biggest deposits of Epsom salt in the solar system.

Because salts are generally colorless or white, some other material must be present as well to account for the reddish color. The identity of that contaminant so far eludes scientists, but sulfur or iron compounds are suspected. Before the Galileo mission, some investigators had predicted that an internal ocean on Europa would probably be quite briny, given that many meteorites contain salts. Europa's surface materials may be revealing the chemistry of a hidden brackish ocean.

Two other Galileo instruments have also bolstered the oceanic hypothesis. The photopolarimeter-radiometer has measured temperatures across the satellite's surface. Higher latitudes are anomalously hot at night (by about five kelvins) compared with equatorial regions. This deviation could be confirmation that in addition to the weak external heating by the sun's rays, Europa has a strong internal heat source—namely, tidal flexing.

One of the most fascinating indications of Europa's present interior state has come from the Galileo magnetometer team. The Galilean satellites are immersed within the powerful magnetic field of Jupiter. Measurements of the ambient field in the vicinity of Europa show deviations associated with the satellite. These deviations might be explained if Europa has an intrinsic magnetic field, but the magnetic axis would need to be tilted at an unusually steep angle to the rotation axis. Alternatively, Europa's subsurface might be an electrical conductor, responding to the time-varying Jovian magnetic field with an induced field of its own. In this scenario the internal conductor must be as conductive as salty seawater.

Surprisingly, the magnetometer also detected a similar field near Callisto, a satellite with a heavily cratered surface that provides no hint of a subsurface ocean. An exciting possibility is that all the solar system's large icy satellites possess salty oceans within, vestiges of their warmer pasts. Galileo's final Europa flyby, planned for this coming January, will be dedicated to determining the source of the field.

Theory and observation have combined to provide a strong self-consistent case for a global ocean within Europa today. But its existence is not unequivocally proved. Warm subsurface ice could mimic many of the effects of an internal ocean. Although the satellite's surface is sparsely cratered and probably geologically young, searches for definitive evidence of ongoing geological activity have been fruitless. Europa might have had an ocean in the recent past that is now frozen solid. There is only one way to know for certain: return a spacecraft to Europa and this time go into orbit.

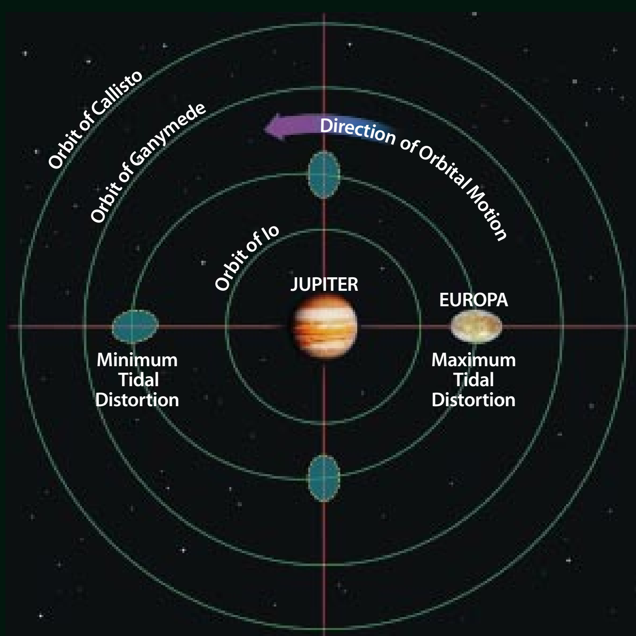
That is just what the National Aeronautics and Space Administration is planning to do. The Europa Orbiter mission could be launched as early as November 2003 and would enter Jupiter's orbit three years later. About two years after that, it would go into orbit around Europa at an average altitude of just 200 kilometers. Precise tracking of its position and altitude would map the gravitational field and shape of Europa in enough detail to track the ebb and flow of tides as the moon trundles around Jupiter. If Europa does have a subsurface sea, the moon's surface should rise and fall 30 meters every 3.6-day orbit; otherwise the tidal bulge will change by just one meter. In this way, the Europa Orbiter would provide the definitive test for an ocean.

Meanwhile the spacecraft's camera would photograph the satellite, and its radar would probe the subsurface for any shallow melt zones. Depending on the ice temperature and purity, the radar signal might even be able to penetrate Europa's ice shell to detect an ocean beneath, in the way Antarctica's Lake Vostok was recently mapped by radar below four kilometers of cold glacial ice [*see box on next page*].

NASA/JET PROPULSION LABORATORY; PAUL GEISSLER AND MOSES MILAZZO *University of Arizona*

BULL'S-EYE SHAPE of the impact site Tyre Macula—one of the few large craters on Europa—hints at the presence of liquid water. The central depression is about 40 kilometers across. The surrounding rings are fractures created as the crater collapsed inward. Small secondary craters, gouged by debris from the impact, pock the surface. The black lines mark gaps in the data.

Life as we know and understand it requires three basic ingredients: energy, carbon and liquid water. Europa could have all three. Tidal flexing should heat the rocky mantle and lead to volcanism on Europa's ocean floor. At volcanic regions on Earth's ocean floors, water circulates through hot rock and emerges rich in chemical nutrients. Biological com-



TOM MOORE

ORBITAL CHOREOGRAPHY of Jupiter's largest satellites coerces Europa into an elliptical orbit. As a result, Jupiter's tidal forces, which stretch Europa into an oblong shape, are stronger at some points in the moon's orbit than at others. (The orbits, moon, planet and tidal effects are not to scale.)

The Lake That Time Forgot

by Frank D. Carsey and Joan C. Horvath

If ever there were a middle of nowhere, Lake Vostok in Antarctica would be it. To get there, one would first have to go to the eponymous Russian scientific base, a place famed for its climate—widely regarded as the world's worst. Then one would have to drill four kilometers straight down. There, cut off from the outside world for the past several million years, is a body of fresh water roughly the extent of Lake Ontario and twice as deep. It may be the closest thing on Earth to the putative ocean of Europa.

The first indication of the lost lake came in the 1970s from aircraft-borne sounding radar, which can penetrate ice and reflect off the underlying rock or water. The strength of the reflected signal and the flat geometry of the under-ice surface clearly revealed water, which was confirmed by reexamination of older Russian seismic data. But researchers only fully comprehended the true size of the lake in 1996, after the smooth expanse of its icy roof had been probed by the European Remote Sensing Satellite. So far no one has drilled into it, although plans are afoot.

The top of the ice is at about 3,700 meters (12,000 feet) altitude, and the lake surface itself is just below sea level. Judging from the contours of the surrounding bedrock, the lake basin may be a tectonic rift—a ruptured area of Earth like those filled by Lake Baikal and the Red Sea. And why is water there, rather than simply more ice? Some geological evidence suggests the presence of a hot spot similar to (but smaller than) that responsible for building the Hawaiian Islands. But even without a hot spot, the trickle of heat from Earth's interior is sufficient to reach the local melting point because of the insulating effect of the ice. In fact, under-ice lakes are not uncommon in Antarctica; Vostok is simply the largest.

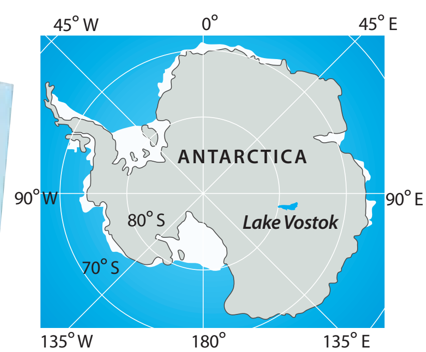
At about the same time Russian and British scientists were mapping Vostok, events elsewhere were revealing how precious its pristine waters could be for science. Microbes were turning up in harsh environments—around deep-sea volcanic vents, in shallower ice-covered Antarctic lakes, in alkaline lakes like California's Mono Lake—that had only one thing in common: the presence of liquid water. Meanwhile the Galileo spacecraft began finding that Europa might have its own ocean under the ice. The depth of the ice cover on Vostok and Europa is similar; except for the lower pressures on Europa (its gravity is about one seventh as strong as Earth's), conditions could be comparable. If life could colonize Lake Vostok, so the thinking goes, then maybe it could find a niche in Europa.

Three years ago we and others at the Jet Propulsion Laboratory proposed exploring both Lake Vostok and Europa using the same basic approach. Vostok would benefit from technology developed for Europa, whereas a Europan explorer could go through its paces near to home. Along with experts at the Woods Hole Oceanographic Institution and the University of Nebraska, we have investigated the possibility of a pair of devices: a "cryobot," which melts its way through the ice, and a small submarine, or "hydrobot," which searches for life and makes other measurements.

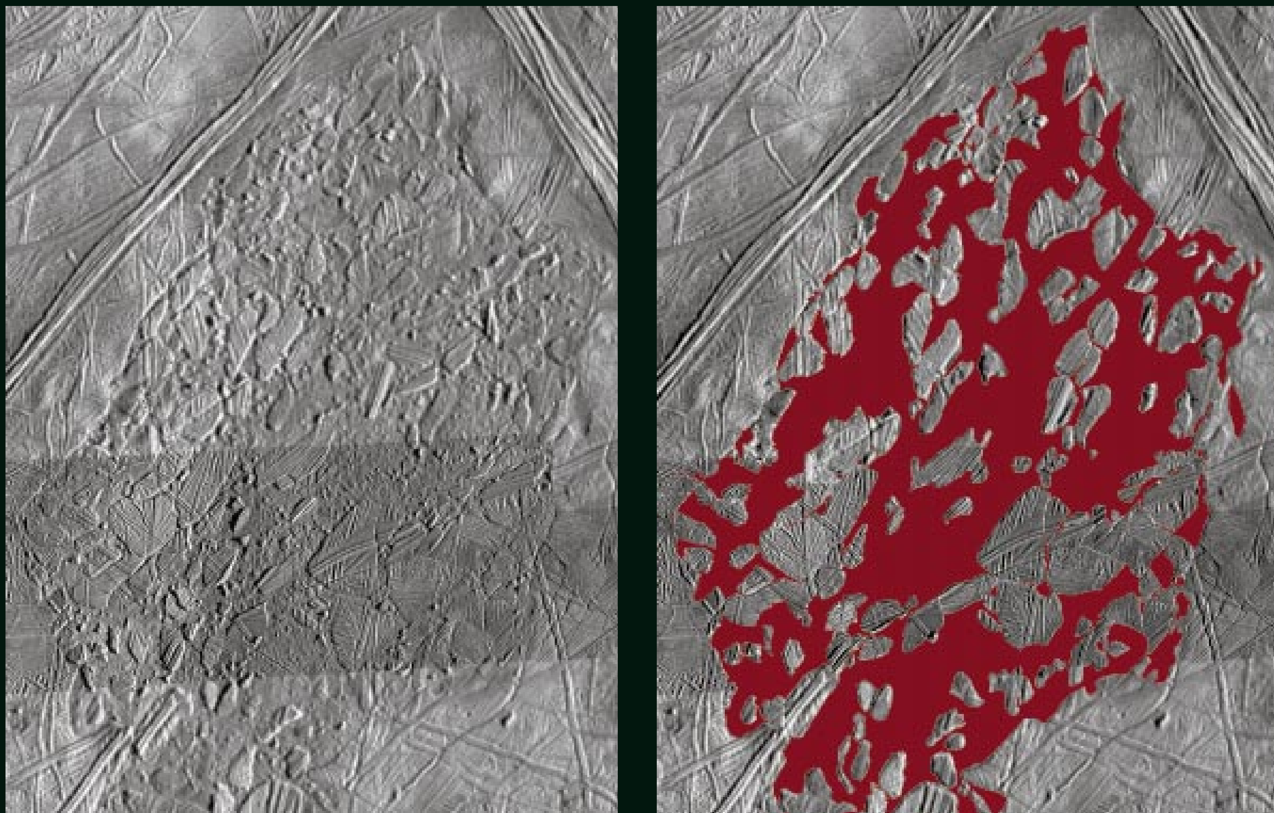
Needless to say, the design will be a challenge. The high pressures in the subsurface seas—which exceed those on the deck of the sunken *Titanic*—seem to demand a large and heavy armored hydrobot, but a large hydrobot would be difficult to send to Europa. The hydrobot must be autonomous and able to respond to a complex environment with cracks, rocks and so on. Its tiny onboard chemistry laboratories must survey the environment and search out microbes, even if they are utterly unlike those seen elsewhere. And both devices must be fully sterilized so they do not contaminate the water with commonplace microbes. Meeting all these demands is beyond the current state of the art in ice coring and miniature submersibles. But engineers are optimistic. The plan is to start exploring Lake Vostok as early as 2003 and Europa perhaps a decade later.

FRANK D. CARSEY and JOAN C. HORVATH lead the Europa/Lake Vostok Initiative at the Jet Propulsion Laboratory of the California Institute of Technology in Pasadena, Calif.

TOM MOORE; SOURCE: FRANK D. CARSEY AND MARTIN J. SIEGERT *University of Bristol*



LAKE VOSTOK is tucked away in an East Antarctic rift valley and covered by about four kilometers of slowly moving ice. Above the lake, the ice floats much as an iceberg does (*left*); to support a slight rise of the ice surface, the lake surface slopes down by about 400 meters from south to north. On the bottom may be sediments. The Russian Vostok station is directly above the south end (*red dot*). (The vertical scale is distorted.)



NASA/JET PROPULSION LABORATORY; CYNTHIA PHILLIPS *University of Arizona (left)*; NICOLE SPAUN *Brown University (right)*

LIKE A JIGSAW PUZZLE, Conamara Chaos can be pieced back together. The Galileo spacecraft saw a jumble of ice blocks jostled and twisted within a frozen icy matrix (*left*). In their reconstruction (*right*), scientists have identified the matrix (*red*) and restored the ridge-topped ice blocks as best as possible to their original positions. But more than half of the pieces have gone missing, converted into matrix. The gnarled region testifies to the geologic vivacity of Europa.

munities thrive at these warm oases. They do, however, depend on the surface ecosystem to a large extent; most notably, oxygen dissolved in the seawater comes from photosynthesis [see "Hot Springs on the Ocean Floor," by John M. Edmond and Karen von Damm; SCIENTIFIC AMERICAN, April 1983]. Europan deep-ocean life, on the other hand, would be utterly on its own. The available chemical-energy resources would be very limited. Although microbial life might make do, biologically complex and diverse organisms of the type that inhabit Earth's oceans probably could not.

If the Europa Orbiter mission confirms the existence of a subsurface ocean, the next logical step would be to examine the surface in situ. A small robotic lander could analyze a scoopful of ice for organic compounds. Ultimately, it may be possible for a robotic submarine to melt a path through the ice shell. Europa's briny waters, now surmised only by indirect means, would then be known firsthand. It might turn out that we are not alone in the solar system after all. SA

The Authors

ROBERT T. PAPPALARDO, JAMES W. HEAD and RONALD GREELEY have worked together on the Galileo imaging team for several years. Pappalardo learned to appreciate Jupiter's satellites during the 1979 Voyager encounters, when he was in high school. Now a research associate at Brown University, he has also worked with various science museums to develop shows and exhibits on planetary discovery. Head began his career helping to choose Apollo landing sites and train astronauts. Since that time, he has been a geology professor at Brown and a participant in nearly every major planetary mission. He has collaborated with Russian scientists for several decades, beginning when the Iron Curtain was as much a scientific barrier as a political one. Greeley is another veteran of planetary science. He began to work for NASA while on military assignment in the pre-Apollo days. Seeing how geological principles could be applied to non-Earth objects—still a new idea at the time—he stayed on at the space agency. He is now a professor at Arizona State University.

Further Reading

GEOLOGY OF EUROPA. Baerbel K. Lucchitta and Laurence A. Soderblom in *Satellites of Jupiter.* Edited by David Morrison. University of Arizona Press, 1982.

EVIDENCE FOR A SUBSURFACE OCEAN ON EUROPA. Michael H. Carr et al. in *Nature,* Vol. 391, pages 363–365; January 22, 1998.

EUROPA: INITIAL GALILEO GEOLOGICAL OBSERVATIONS. Ronald Greeley et al. in *Icarus,* Vol. 135, pages 4–24; September 1998.

THE NEW SOLAR SYSTEM. Fourth edition. Edited by J. Kelly Beatty, Carolyn Collins Petersen and Andrew Chaikin. Cambridge University Press, 1998.

The Galileo project site is at www.jpl.nasa.gov/galileo on the World Wide Web.

The Europa Orbiter site is www.jpl.nasa.gov/ice_fire//europao.htm on the World Wide Web.

Why Things Break

Scientists have known for most of this century that chemistry is responsible for whether a solid shatters or bends. But only now are they finding a way to predict which type of failure will win

by Mark E. Eberhart

For most people, it is a tragedy when something breaks or bends, but for me this is often a highlight of my day. When shattered glass catches my eye, I find myself reassembling the shards and tracing the path of the fracture backward to its origin. Other times, I will stop next to an old tree to chronicle the way its growth has slowly twisted the posts of a wrought iron fence. My interest in the way things break is not rooted in a preoccupation with destruction but rather in the knowledge that all technology is founded on whether materials fail in a brittle manner, like glass, or in a ductile way, like iron.

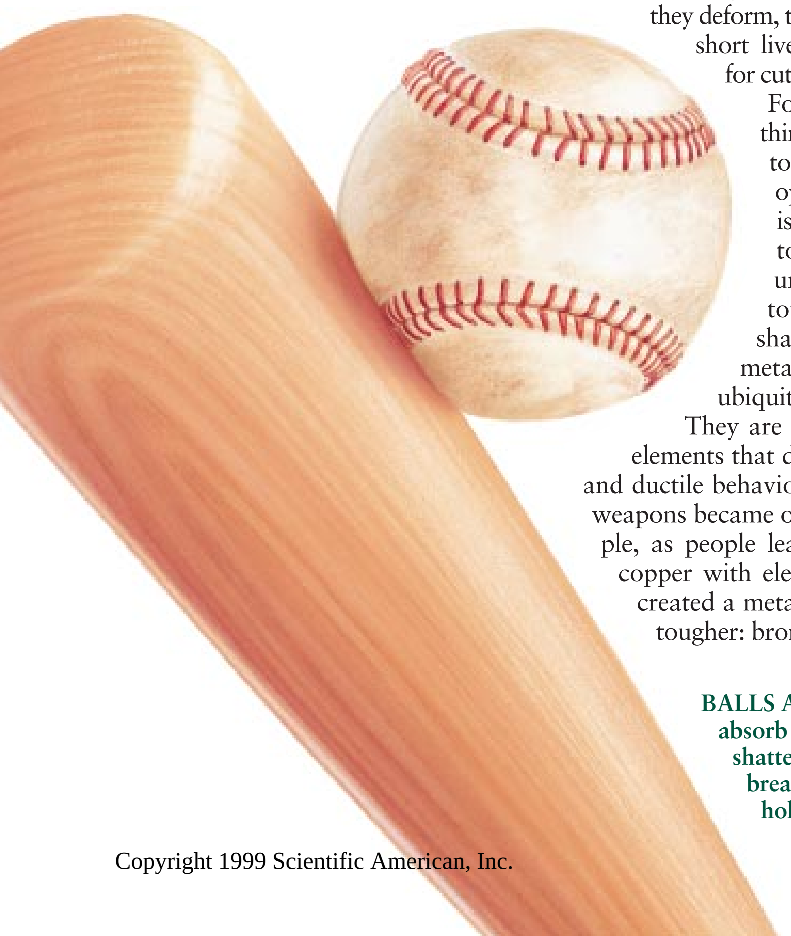
In fact, the history of technology is linked in large part to the ability to exploit these two forms of failure. Manipulating brittle failure in minerals like flint launched human beings into our first technological era—the Stone Age—about 2.5 million years ago. More recently, about 5,000 years ago, the discovery of substances such as gold and copper, which resist brittle failure, led the way into the early Metal Age. Ancient artisans found these ductile metals good for making jewelry and other ornamentation because they are soft and can be easily stretched or pounded with a mallet. But although they are tough and absorb huge amounts of energy as they deform, these materials have short lives when fashioned for cutting or scraping.

For building so many things—from swords to skyscrapers—the optimum compound is both hard enough to hold its shape under stress *and* tough enough not to shatter. That is why metals have become ubiquitous in our culture. They are the only group of elements that display both brittle and ductile behavior. Stone tools and weapons became obsolete, for example, as people learned that mixing copper with elements such as tin created a metal both harder and tougher: bronze.

Even harder than bronze are alloys of carbon and iron, which eluded widespread use until about 1000 B.C., when early metallurgists invented furnaces that burned hot enough to extract the iron from its ore. Although they are hard, iron-carbon alloys can absorb little energy before fracturing. Early on, metallurgists learned that blowing air through this compound reduced its carbon content, which made it more ductile—and resulted in the world's first steel. Ever since, technology has progressed hand in hand with the ability to design materials with varying degrees of ductile and brittle behavior.

Fatal Flaws

Despite the ancient connection between technological progress and the way things break, it is only in this century that a scientific basis for understanding exactly *why* things break has surfaced. Even now, however, many of the details remain shrouded in microscopic complexities. For example, it is not understood why three atoms of hydrogen per one million atoms of iron can make normally ductile steel dangerously brittle. To answer this and other questions, I have spent the past 20 years trying to use the tools of molecular chemistry to predict how a material will break. Eventually I hoped to be able to design materials that break just as they are intended. To do that, I first had to explore why and how chemical bonds break.



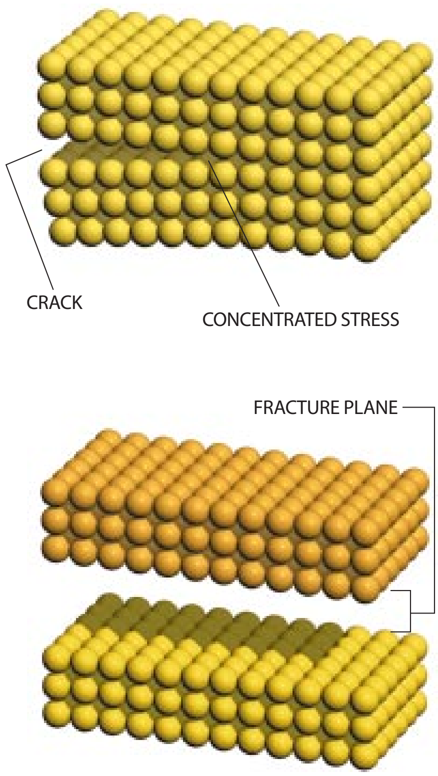
MATTHEW HOLMES

BALLS AND BATS do not break (at least not usually!), because they can absorb the energy of their collision. A glass window, on the other hand, shatters on impact. Exactly why some things stay intact and others break comes down to the elusive behavior of the chemical bonds that hold them together.

MATTHEW HOLMES

A scientific understanding of materials failure developed concurrently with the realization early this century that a solid is a collection of atoms held together by chemical bonds. Chemists first visualized bonds as rods linking pairs of atoms. The structure of a solid is then seen as an array of stacked polyhedra, such as cubes or octahedra, in which the polyhedral corners are the positions of the atoms and the edges correspond to the chemical bonds. When this array is stretched, each bond responds by elongating and bearing a portion of the extension. When strained beyond some critical point, the bond breaks; when enough bonds break, the solid cracks.

A problem confronted the new science of materials failure when researchers noted that even the highest-strength materials fail at stress levels as little as one tenth those required to break chemical bonds. In the early 1920s A. A. Griffith showed that the strength of a material is not a direct consequence of the strength of its bonds but of weaknesses created by defects within its structure. These defects, or cracks, can be microscopic or visible to the naked eye, depending on how the material has been processed. Griffith realized that when stretching a material perpendicularly above and below a crack, the bonds at the crack tip endure more elongation than the bonds elsewhere along the defect. When one bond is stretched beyond its breaking



BRITTLE MATERIAL breaks along a microscopic crack. When two sheets of atoms are pulled apart along such a flaw, stress concentrates in the tip of the crack. In a material such as glass, the chemical bonds across the tip break first. The crack then opens like a zipper, and the sheets separate along a fracture plane. If several cracks run at once, the glass shatters.

point, stress concentrates on the remaining bonds, which in turn break, and the crack tears open like a zipper [*see illustration above*]. The result: brittle fracture.

Artists and engineers exploit the brittle properties of materials to direct cracks where they want them. For example, the force it takes to break a sheet of glass along a scratch is far less than that required to split a smooth sheet. When strained, the bonds along the bottom of the groove experience concentrated stress and so break before those elsewhere in the structure.

Ductile materials such as copper, on the other hand, will not break along a shallow crack. In 1973 James R. Rice, now at Harvard University, and Robert G. Thompson of the National Institute of Standards and Technology suggested that the same force that tears open a crack in a brittle material will blunt a crack in a ductile one. The pair proposed that the bonds break first between planes inclined to the crack tip, but no new defect forms. Instead these inclined layers of atoms slide across one another to relieve stress, linking new pairs of atoms in the process [*see illustration on next page*]. Called slip, this process relies on the ease with which bonds form and break along this plane.

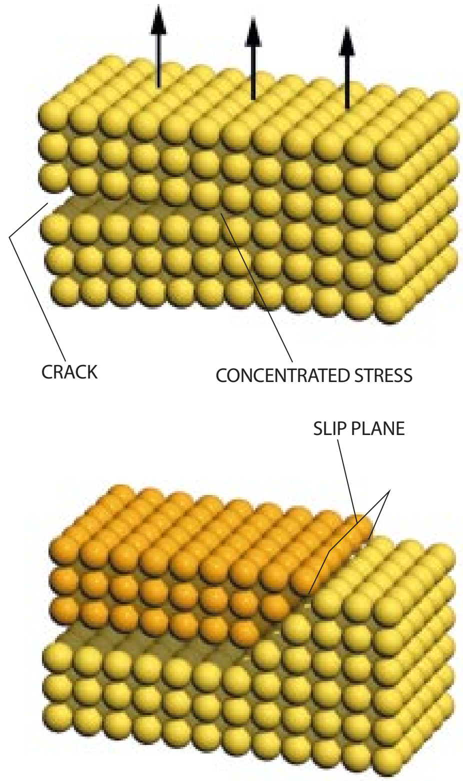
Intrinsically ductile or brittle behavior thus boils down to whether the bonds across a crack break before the bonds across the slip planes do. Metallurgists could determine which planes fracture or slip by examining materials under electron microscopes. But exactly why one material behaves differently from another remained locked in the mysteries of chemical bonds, which turned out to be more complex than scientists originally imagined.

The conventional representation of the chemical bond—rods connecting adjacent atoms—can suitably describe many ways that molecules behave, but it makes for a remarkably inefficient explanation of how solids break and bend. Even if you could stand on the cluster of protons and neutrons of an atom's nucleus, it's not as though you would be able to walk across a bridge to a neighboring atom. Chemical bonds actually owe their tendencies to the varying density of a material's electronic structure.

The electronic charge is most dense at the nucleus, where the positively charged protons sit. All that exists beyond the nucleus is a haze of charge generated by electrons. This haze is usually most dense in the direction of the closest nucleus where electrons belonging to both atoms overlap. By 1926 physicists had discovered the laws of quantum mechanics that described this distribution of charge in atoms and molecules, but solving the equations for large numbers of atoms would require the help of supercomputers.

Only by the late 1970s had computing become sufficiently advanced for even the most rudimentary theoretical exploration of the way a solid's electronic structure is linked to fracture. By 1990 faster computers allowed physicists to take advantage of the more sophisticated algorithms needed to simu-

CHRIS JONES *The Stock Market*



SLIM FILMS

DUCTILE MATERIAL deforms along a plane inclined to a microscopic crack. Atoms across this inclined plane slide past one another and thus relieve stress on the bonds in the crack. Blunting the crack tip in this way absorbs huge amounts of energy, making ductile metals much safer than brittle ones for use in cars and other structures that are intended to withstand collision.

late breaking or bending. This advance proved invaluable to researchers such as Gregory B. Olson and his colleagues at Northwestern University's Steel Research Group. Olson organized the group in 1985 to engineer the tools needed to design ultrahigh-strength steels by computer.

With computer programs designed by Arthur J. Freeman, also at Northwestern, Olson and his co-workers developed a way to determine the differences in charge density among similar materials. They calculated the charge density of a "virtual" alloy as two planes of atoms pull apart or slide past each other. Using that charge density, they could determine how much energy it required to cause the fracture or slip. Then they would modify the composition of the virtual alloy and run the calculations again. By comparing the energies of the two materials, the team could determine whether each alloy was brittle or ductile. The energy differences they found between virtual alloys now consistently agree with the failure properties metallurgists measure for the actual alloys in the laboratory.

Although Olson and Freeman's calculations showed that it is possible to re-create fracture and slip realistically on the computer, this ability still did not allow us to *predict* how to change an alloy's chemistry to produce ductile or brittle behavior. I wanted to develop just such a theory. In particular, I wanted to predict the right elements to put in a chemical structure to achieve desired changes. Experience has taught us that only certain elements would work, but which ones were they? The answer came down to a revolutionary way of imagining exactly what chemical bonds in a solid look like.

Deep Connections

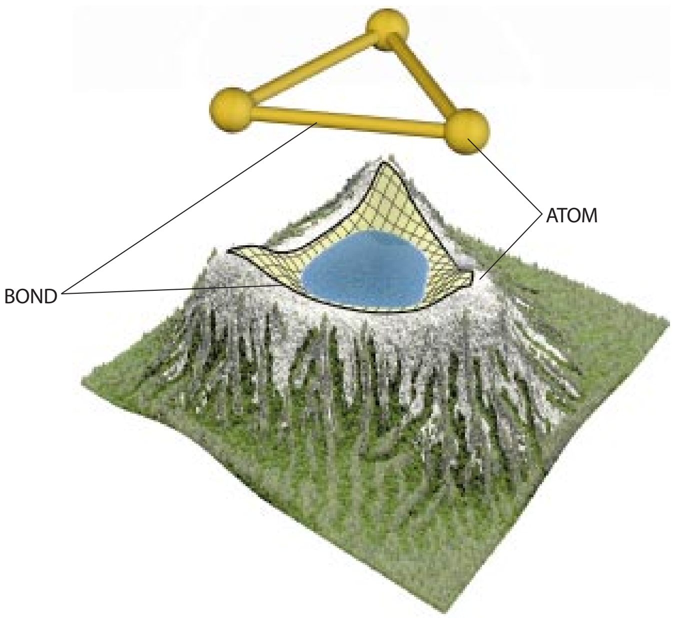
A predictive theory of intrinsic failure would be especially useful to my collaborators who design new alloys at United Technologies Research Center in Hartford, Conn., and at Wright-Patterson Air Force Base in Dayton, Ohio. Such a capability would allow them to improve materials such as nickel aluminide, which the air force wants to use for building jet engines because it is lightweight and, contrary to most metals, gets stronger as it is heated. But as is often the case with high-temperature alloys, nickel aluminide is too brittle to be safe for use in airplanes and other machines. I needed to figure out a way to predict what atoms in the material's structure should be replaced to make it more ductile.

Conventional models describe chemical bonds in terms of the amount of electronic charge located between atoms, but this concept falls short of reality. As atoms move apart, this charge stretches thin but never vanishes. Because the connection of the bond is never broken, this concept fails to describe fracture. Some other feature of the charge density must better represent a bond and how it breaks. Chemist Richard F. W. Bader of McMaster University discovered exactly what this feature is: topology.

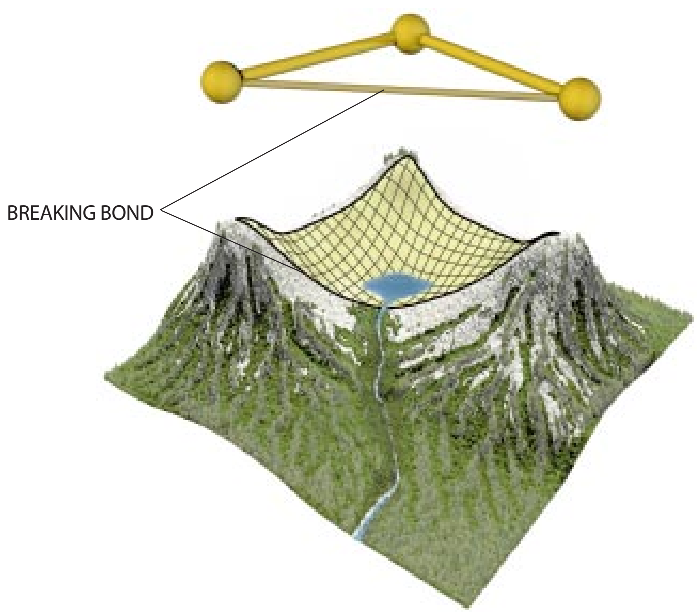
Topology is a branch of mathematics

New View of Chemical Bonds

The conventional model of chemical bonds as rods connecting atoms cannot adequately describe why thing break. In reality, the rods represent a haze of electronic charge. If you pull two atoms apart, the haze of charge stretches thin, but because it never vanishes, there is no indication of when a break occurs. To find out what does disappear when bonds break, I look at the charge density topology, which describes the connections within the groups of atoms.



The charge density in two dimensions is analogous to elevation on a topographic map. A peak represents the most charge, which is at an atom's nucleus, a basin denotes the least charge, and a ridge joining two peaks is a chemical bond. The charge density topology is equivalent to the conventional view of molecular structure because their components correspond one-to-one.



As atoms move apart when a material is stretched, the charge density along the bond will diminish. The bond breaks—and ceases to exist as a topological connection between atoms—when the lowest point of the ridge has dipped below the elevation of the bottom of the basin. —*M.E.E.*

DAVID FIERSTEIN

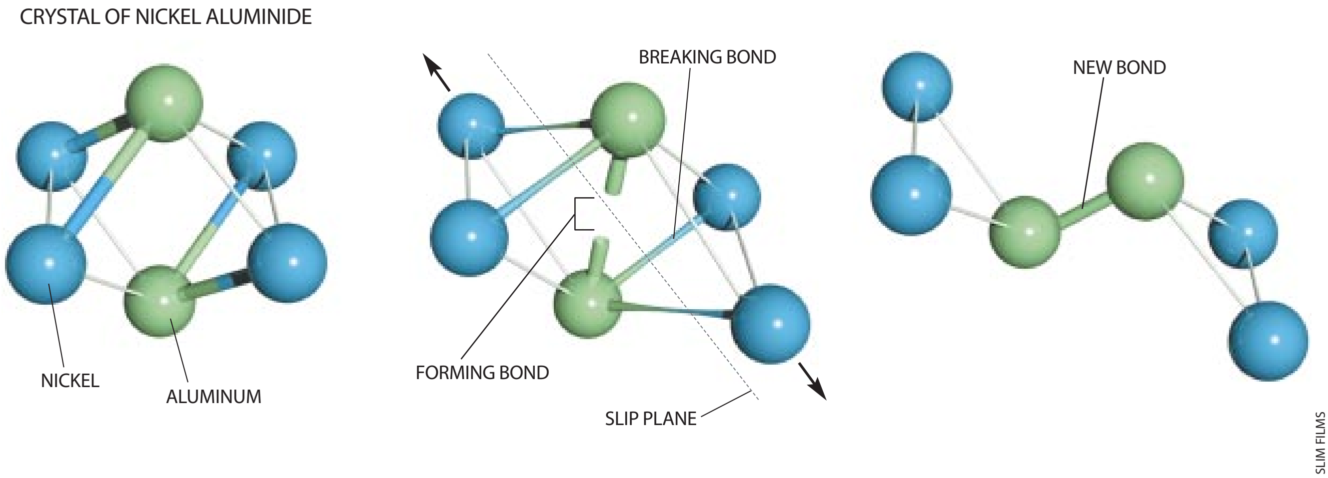
that describes the nature of connections that endure within an object as it is stretched or squeezed. (Cutting or combining shapes destroys the object's original topology.) For example, a teacup and a doughnut are topologically identical. If you use the hole in a clay doughnut to form a handle, you can sculpt the doughnut into a teacup without cutting the clay. On the other hand, a ball of clay cannot be molded into either a doughnut or a teacup without punching a hole in it and separating parts that had previously been connected.

Bader used his revolutionary ideas about chemical bonds to analyze organic molecules, but I found in his observations a fascinating way to look at a metallic solid. Fracture is a process that changes the nature of the connections within an object, so it made sense to describe it using topology. But first I had to show for solids, just as Bader had for molecules, that the topological picture of bonding connected the atoms in the same way as the conventional view [*see box at left*].

A topological connection between atoms can best be explained by comparing charge density to a topographic map of a mountain range. In this picture the altitude directly corresponds to the density of the charge: peaks represent areas of most charge, basins are points of least charge, and so on. Two atoms are topologically connected if there is a ridgeline of charge density between these peaks. Such ridgelines correspond to the rods of the conventional picture and represent the chemical bonds between atoms.

For four years, I performed calculations on simple metals and alloys to show that the topological view of bonding connected the same atoms as did the conventional picture. Topology tells us that we do not need to examine the entire charge density to map the terrain. We need to find only those points where the terrain flattens out, which are peaks, basins and passes. If you know only the positions of these flat spots, or critical points, you can interpolate the terrain between them. In particular, if you know the positions of two peaks and a pass between them, you can safely assume that a ridgeline—or chemical bond—runs from one peak through the pass and to the other.

Demonstrating the validity of the topological view of chemical bonds in a solid was straightforward, but at that point I knew only which atoms were



CHARGE DENSITY TOPOLOGY reveals exactly where and when bonds break and form as a metallic solid deforms—something that conventional models alone never fully explained. No one was sure, for example, that a bond forms between the two aluminum atoms in a crystal of nickel aluminide as it stretches along a slip plane. The charge needed to build this bond comes from the breaking of links between nickel and aluminum atoms. Manipulating this charge transfer is key to making this alloy more ductile.

connected. I still knew nothing about how easy it would be to break the bonds. To answer this question, I needed to look at the shape of the terrain around the critical points. This shape can be characterized by the point's principal curvatures, which describe the two perpendicular directions in which the altitude experiences its most extreme rate of change. The principal curvature is negative when the altitude decreases, as from a mountain peak.

Conversely, positive curvature occurs in any direction in which altitude increases. At a pass between two mountains—the center of the ridgeline that represents a bond—the altitude will rapidly increase in the direction of the nearby peaks and decrease in the perpendicular direction. The pass has both a positive and negative principal curvature and is called a saddle point.

To describe fully the charge density, we need to extend this picture to three dimensions. Every critical point has three principal curvatures. For example, a saddle point with two negative and one positive principal curvature defines a three-dimensional bond.

First Predictions

Associating bonds with a well-characterized feature of the charge density made possible the first description of bond breaking as a topological process. When two bound atoms inside a solid are pulled apart, the curvatures along the bond and in two perpendicular directions change. When the curvature along one or both of these directions vanishes, so does the topological connection between the atoms. The key: a bond is broken not when the charge density between atoms vanishes but when the two atoms lose their topological connection.

Using the topological description of bonding, along with the magnitude of the principal curvatures involved, we can form a more quantitative analysis of fracture. Consider a saddle point in two dimensions using the analogy of the mountain range [*see box on opposite page*]. Starting at the pass between two mountains, you could walk in any of four directions, two around each peak, along which your altitude (and therefore the charge density) would not change. If four people started at the pass, and each took off in a different one of these directions, their paths as seen from above would form an X. A plane containing these X-shaped paths makes an acute angle with the direction that most steeply descends toward a lake in the basin below, which is the area of least charge density. This angle turns out to be related to the ratio of the two principal curvatures.

Pulling the two peaks (or atoms) apart removes charge from the bond, just as blasting away rock and dirt would lower the elevation of the pass. The size of the original angle tells us how much dirt can be moved, and as excavation progresses that angle becomes smaller and smaller. As this angle approaches zero, the pass drops below the elevation of the lake surface, which begins to drain. The bond breaks—and the pass ceases to exist—when the angle is equal to zero. By that time the pass has reached the same elevation as the lowest point in the basin, and the last drop of lake water has drained away.

Similarly, a bond could form by adding charge to a minimum. This bond-building process is like trucking in dirt from the excavated pass to form an earth embankment, or ridgeline, through the center of the lake. In short, a bond breaks when charge is taken away from the area around a saddle point; a bond can form when charge is added near a minimum.

The mountain pass analogy is more complex when used to characterize the charge density in three dimensions. The angles used to measure the charge density must now be defined by geometric shapes. (In this case, charge density is more like moving through a bottomless ocean of molasses that is stickier in some directions than others.) Instead of a flat plane containing the four directions you could walk without gaining or losing altitude, we must now visualize a shape that would contain all the directions in which the charge density is equivalent.

If you take the X formed by the two-dimensional directions of equal charge density and rotate it around its axis along the chemical bond, you get two cones positioned point to point. The outside edge of the cone makes an acute angle with a plane positioned perpendicular to the bond and running through the points of the cones. This is the angle that provides a measure of the amount of charge that must be lost from the saddle point to cause the bond to break. As the angle gets smaller, the bases of the cone approach each other and eventually form a disk. As in the two-dimensional

Tough Breaks

When it comes to the safety of a complex structure such as an airplane, sudden failure is bad news. Just ask the passengers and crew who were on board Aloha Airlines's infamous Flight 243. Twenty minutes after take-off on April 28, 1988, cracks along rivets joining sheets of the aircraft's metallic skin violently tore apart. Higher air pressure inside the cabin blew off an 18-foot section of the forward fuselage leaving some 90 travelers to endure an emergency landing of what had become an airborne convertible. The explosion ejected one flight attendant from the plane, but fortunately everyone else survived.

Closer inspections of the aircraft before the accident would have revealed that microscopic cracks around the rivets had grown bit by bit as the aircraft's 19 years of service heaved and stretched its metallic joints. During the final fateful flight, the cracks reached a critical length at which they abruptly unzipped. But until that catastrophic moment, the tiring metal had been tearing slowly only along those cracks, as its designers intended. This ductile deformation relieves stress in the metal by blunting the tips of the cracks. Their slow growth provides the best opportunity to see signs of fatigue before something shatters.

Safety is what drives materials designers to search for ways to add just a touch of ductility to metals that are rigid enough to hold their shape under stresses such as the changing air pressure an airplane experiences in flight. One way to make a material more ductile is to add just the right elements to the base alloy, which for centuries has been based on a painstaking process of trial and error. Only recently has anyone discovered how to predict which elements will best do the job.

Metallurgists have developed a second way to make a brittle material less apt to fail catastrophically: manipulating its microscopic structure. Materials scientists can arrange individual metallic crystals much the way someone packs china for shipping. For example, they can wrap crystals of a brittle material with layers of an intrinsically ductile one, such as copper. Just as covering individual dishes in bubble wrap cushions them from stress, any crack in a brittle metallic crystal will run only as far as its boundary with the ductile copper. Once the best base alloy is chosen, it takes this kind of microstructural design to make the alloy ductile enough to be safe—or at least to offer warning signs before catastrophe strikes. *—M.E.E.*

PASSENGERS SCRAMBLE to exit the exposed cabin of Aloha Airlines Flight 243.

scenario, the larger the starting angle, the more charge must be removed to reduce the angle to zero and break the bond.

The flip side of bond breaking is bond formation, and we must understand both to describe failure. Just as a cone can represent a bond, other geometric shapes can represent other critical points. A minimum, which can become a bond if enough charge is added near the point, is represented by an ellipsoid. In this case, two angles are necessary to specify its shape and to measure the amount of charge, or dirt, that must be transferred from a saddle point to form a bond. The angles also tell you whether it will be easier to build an embankment across the lake in one direction than another.

With unique geometric representations for all a solid's critical points, we can measure exactly when and in what amounts the charge density is changing during bond formation and bond breaking. Whether a material fails by brittle or ductile means depends on which of these processes dominates, so it follows that we should be able to favor one over the other. I applied this line of reasoning to explain the failure properties of nickel aluminide and two closely related alloys, the aluminides of iron and cobalt.

All three of these compounds have identical structures and thus provided the ideal test case for the new approach to describe materials failure. I wanted to explain the difference in properties of the three alloys, which had not been done using conventional models, and to suggest elements that could be added to nickel aluminide to make it more ductile. That meant I had to get original bonds to stay around as long as possible and to encourage new bonds to form along the slip plane as early as possible. That trade-off would entail taking charge from the breaking bonds to form new ones. To figure out in what instances this was possible, I needed new computer programs that would generate the numbers required to map out the charge density and to evaluate its changing topology.

James M. MacLaren of Tulane University developed just the tools that I required to calculate the charge density for the three aluminides and, most important, to identify the critical points and the various angles needed to describe them. What I first discovered in the computer simulations was consistent with the failure properties of these metals that had been discovered in experiments. For example, iron aluminide, known to be the most ductile of the three alloys, showed the most charge in its bond around the saddle point between iron and aluminum atoms. This aluminide also showed the flattest minimum between adjacent aluminum atoms, thereby requiring the least charge to build a bond there.

The suggestion that the failure properties of these three alloys could be reduced to knowing the shape of the charge density around only two points allowed me to take the next step. I predicted that I could alter the failure properties of nickel aluminide by substituting an element for some of the nickel atoms that directed more charge along the nickel-aluminum bond to be available for building new bonds between aluminum atoms in the minimum. This

AP/WIDE WORLD PHOTO

charge redistribution would refine the shape of the charge density to that of a more ductile material.

Because every element has a specific shape to its charge in a given environment, it was a simple matter to identify iron as the best substitute. Thinking back to the analogy of the mountain range, I knew that every element makes a mountain with different slopes falling away from its peak. Standing next to a mountain of aluminum, a mountain of iron puts more rock into the pass and forms a flatter basin than does a nickel mountain. With iron, I have enough rock to remove it from the bond and build a new ridgeline between aluminum atoms in the basin. A cobalt mountain, on the other hand, contributes too little rock to the pass to build the ridgeline.

By the time I had made my predictions, the empirical search for alloying elements to improve nickel aluminide had been under way for nearly 15 years, so there was every reason to believe that other researchers already knew whether iron produced improvements in its ductility. At a meeting late last year, I discovered that relevant experiments showed that 10 percent iron substituted for nickel has exactly the predicted effect.

Predicting the Future

Although my predictions came too late to actually influence the alloy development of nickel aluminide, celebration is still in order. A theory for creating materials that behave just as they are intended could revolutionize—even supplant—the conventional trial-and-error searches that eat up billions of dollars and years of researchers' time.

The search has already begun for new alloys that are even lighter and stronger—and more capable of retaining these properties at even higher temperatures. These improved alloys will find uses in supersonic and hypersonic aircraft sometime after the year 2010. But the development program for these materials will proceed differently than all others in human history.

Rather than searching blindly for a base alloy with the ideal set of intrinsic properties, materials designers will use computers to calculate the charge density of candidate base alloys. From this information they will determine how the charge density must be changed to produce desired properties and then make predictions as to which alloying elements will produce these changes. For the first time, a new alloy will be designed beginning with its electronic structure.

I just wonder if they will christen the first airplane made from this alloy by breaking a bottle of champagne across its nose. If so, I hope I can have the broken bottle for closer study. SA

The Author

MARK E. EBERHART became intrigued with applying chemistry fundamentals to problems of materials failure as an undergraduate chemistry major at the University of Colorado. His interest grew out of attempts to strengthen the kayaks he built, making them less likely to shatter against river boulders. This interest carried him to the Massachusetts Institute of Technology, where he received a Ph.D. in materials science in 1983. Since that time, he has worked to develop more robust models of chemical bonding useful in the design of materials with predictable intrinsic properties. Now an associate professor of chemistry and geochemistry at the Colorado School of Mines, he directs the school's Center for Computation and Simulation for Materials and Engineering.

Further Reading

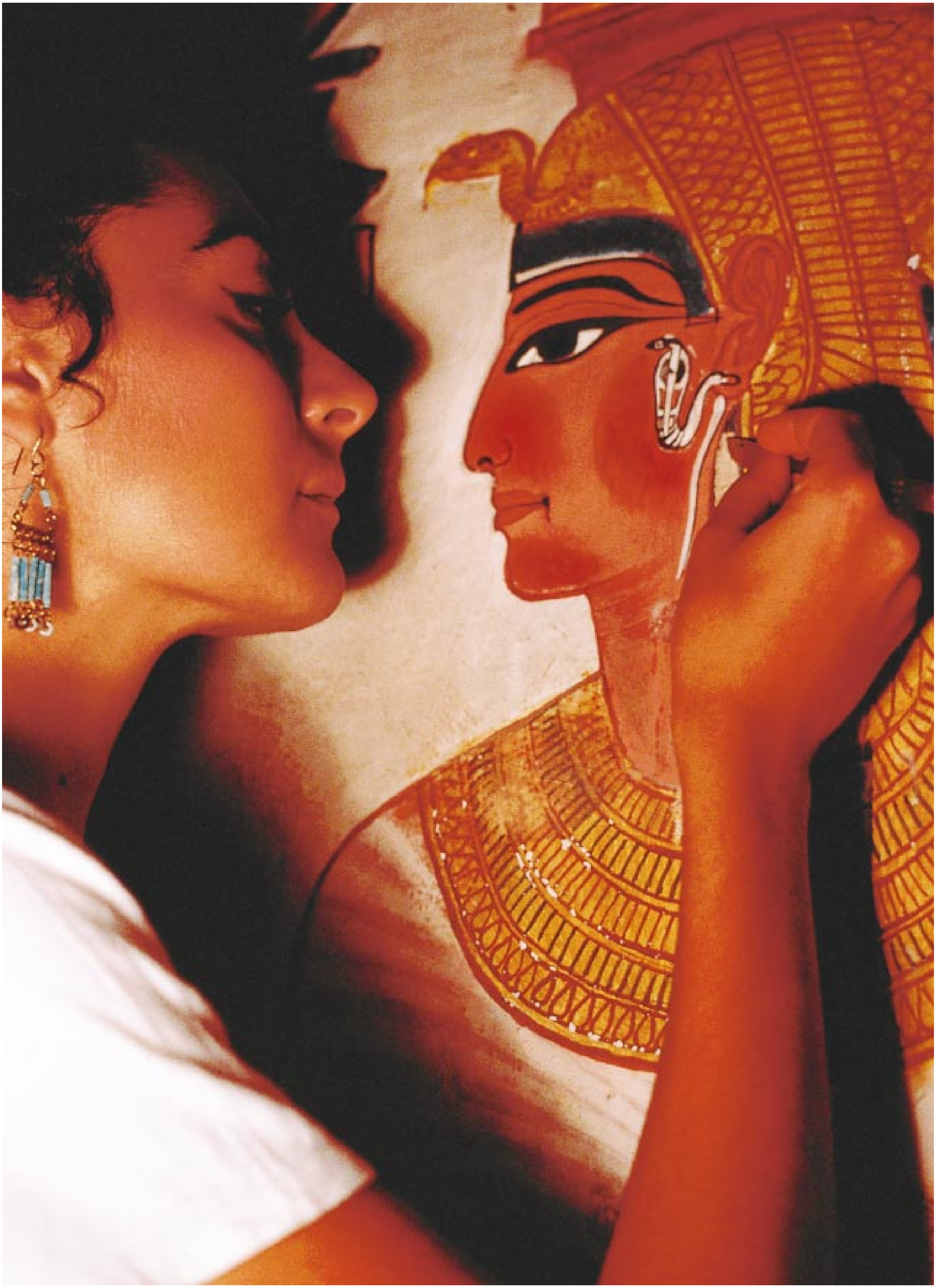
Atoms in Molecules: A Quantum Theory. Richard F. W. Bader. Oxford University Press, 1994.

Computational Metallurgy. Mark Eberhart in *Science*, Vol. 265, pages 332–333; July 15, 1994.

Stuff. Ivan Amato. BasicBooks, 1997.

The Visualization and Use of Electronic Structure for Metallurgical Applications. M. E. Eberhart and A. F. Giamei in *Materials Science and Engineering A: Structural Materials*, Vol. 248, No. 1, pages 287–295; 1998.

Further information on molecular structure is available at www.chemistry.mcmaster.ca/faculty/bader/ on the World Wide Web.



G. ALDANA *J. Paul Getty Trust*

The tomb of this ancient Egyptian queen is testament to the great love of Pharaoh Ramses II. Its preservation is testament to advances in conservation

Preserving Nefertari's Legacy

by Neville Agnew and Shin Maekawa

Little is known about Nefertari, favorite wife of Ramses II, the pharaoh who ruled Egypt from about 1290 to 1224 B.C. But it is clear she was beloved by her husband. He ensured that the statue dedicated jointly to Nefertari and the goddess Hathor at Abu Simbel was on the same scale as his, an honor no other Egyptian queen achieved. His names for Nefertari bespoke great love as well: "lady of charm," "sweet of love," "beautiful of face," "for whom the sun shines." And after her death, Ramses II bestowed on Nefertari a final, spectacular tribute: even though she was not of royal lineage, he buried her in a decorated tomb in the Valley of the Queens.

G. ALDANA J. Paul Getty Trust

The wall paintings in Nefertari's tomb are among the most beautiful of all pharaonic funerary art. As in other tombs, the images of Nefertari are solely about her journey to the afterlife and her encounters with Osiris and Isis, among other deities; no paintings depict her everyday life with Ramses II or her six or seven children. But even as they describe a ritualized journey—following a strict formula laid out in the 174 or so chapters of the Egyptian Book of the Dead—the paintings in Nefertari's tomb are unique in their vivid color and detail and richness.

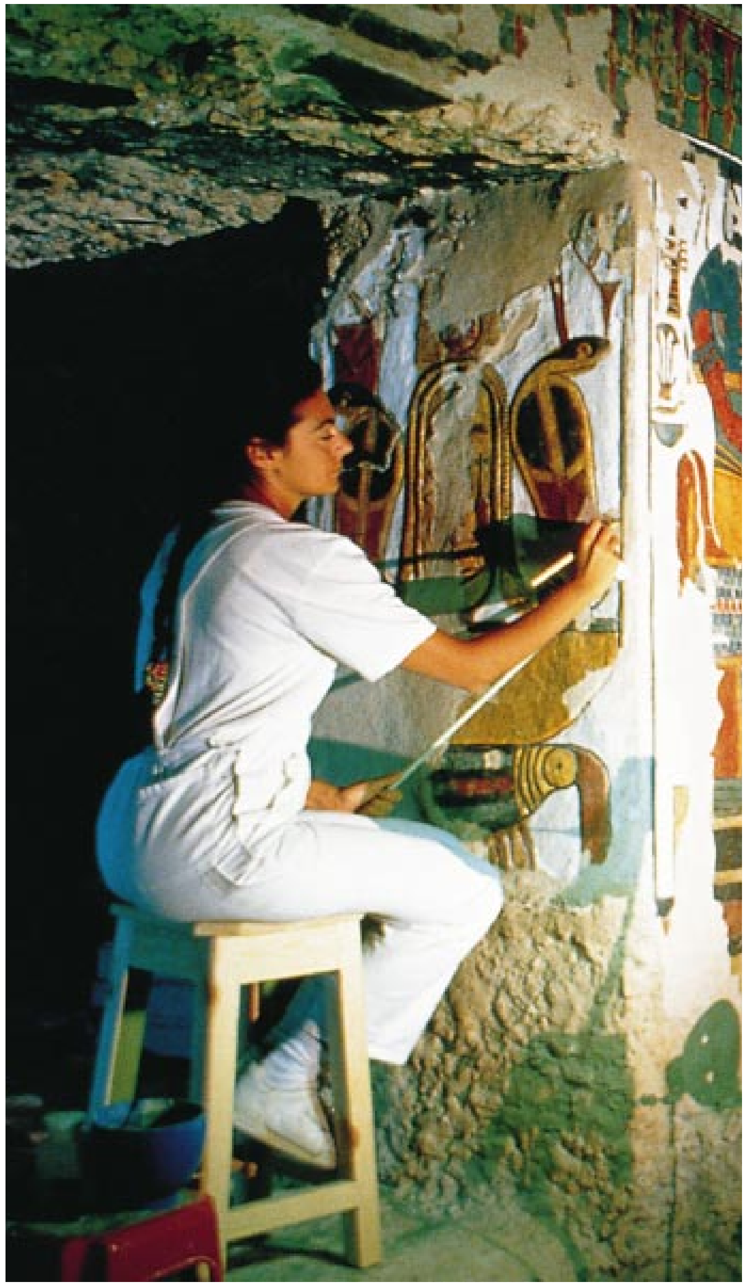
Ramses II's devotion to his queen may have protected her as she moved into the afterlife, but it could not protect her as she moved through the ages. When Italian archaeologist Ernesto Schiaparelli discovered the tomb in 1904, it had already been broken into and looted. The treasures that were to accompany Nefertari in her death were gone, her sarcophagus smashed and her mummy spirited away.

The tomb's wall paintings were severely disturbed as well, but this was the result of natural processes, not of grave robbers. Salt had leached from the limestone bedrock into which the tomb was carved and had crystallized below the painted plaster, destroying a large proportion of the paintings. Over the next decades, visitors to the spectacular tomb inadvertently accelerated this deterioration: the main culprit was most probably their incessant touching of the fragile surfaces, but moisture from their breath and sweat may have contributed as well. Archaeologists and art historians became increasingly concerned, and in the 1920s the Metropolitan Museum of Art in New York City sponsored extensive photographic documentation of the murals. (This record supplemented 132 glass plate negatives that Schiaparelli's photographer had assiduously made in 1904 and 1905, as well as other photographic records that had been made in the intervening years.) But the paintings remained in danger; finally, they were so obviously imperiled that the Egyptian government closed the tomb to the public in the late 1930s.

Nefertari's lovely legacy then sat in dusty silence, visited only by a few scholars. Beginning in the late 1970s, several groups—including the United Nations Educational, Scientific and Cultural Organization (UNESCO), the International Center for the Study of Preservation and the Restoration of Cultural Property, and Cairo University—conducted a series of studies about the condition of various important tombs. The research brought to light, again, the deplorable state of the Nefertari wall paintings and ultimately led conservators at the Getty Conservation Institute and the Egyptian Antiquities Organization to propose saving the remaining paintings—and potentially reopening the tomb to the public.

Between 1986 and 1992 the two organizations conserved the paintings, employing advanced tools and techniques. The

PAST AND PRESENT come face to face as conservator Lorenza D'Alessandro examines a painting of Queen Nefertari (*opposite page*), assessing how best to save it. As its colorful entrance reveals, the tomb of Nefertari in the Valley of the Queens contains some of the most spectacular paintings of its era (*above*).



SALT CRYSTALS, which formed as water infiltrated the limestone into which the tomb was carved, forced the plaster away from the bedrock and destroyed a large proportion of the paintings before the conservators began their work (*above, top*). Earlier efforts at restoration had tried, unsuccessfully, to stem the damage by holding the plaster in place with gauze (*above, bottom*). This time the approach was thorough: conservators removed the salt crystals, reattached the plaster to the walls and cleaned the paintings (*right*).

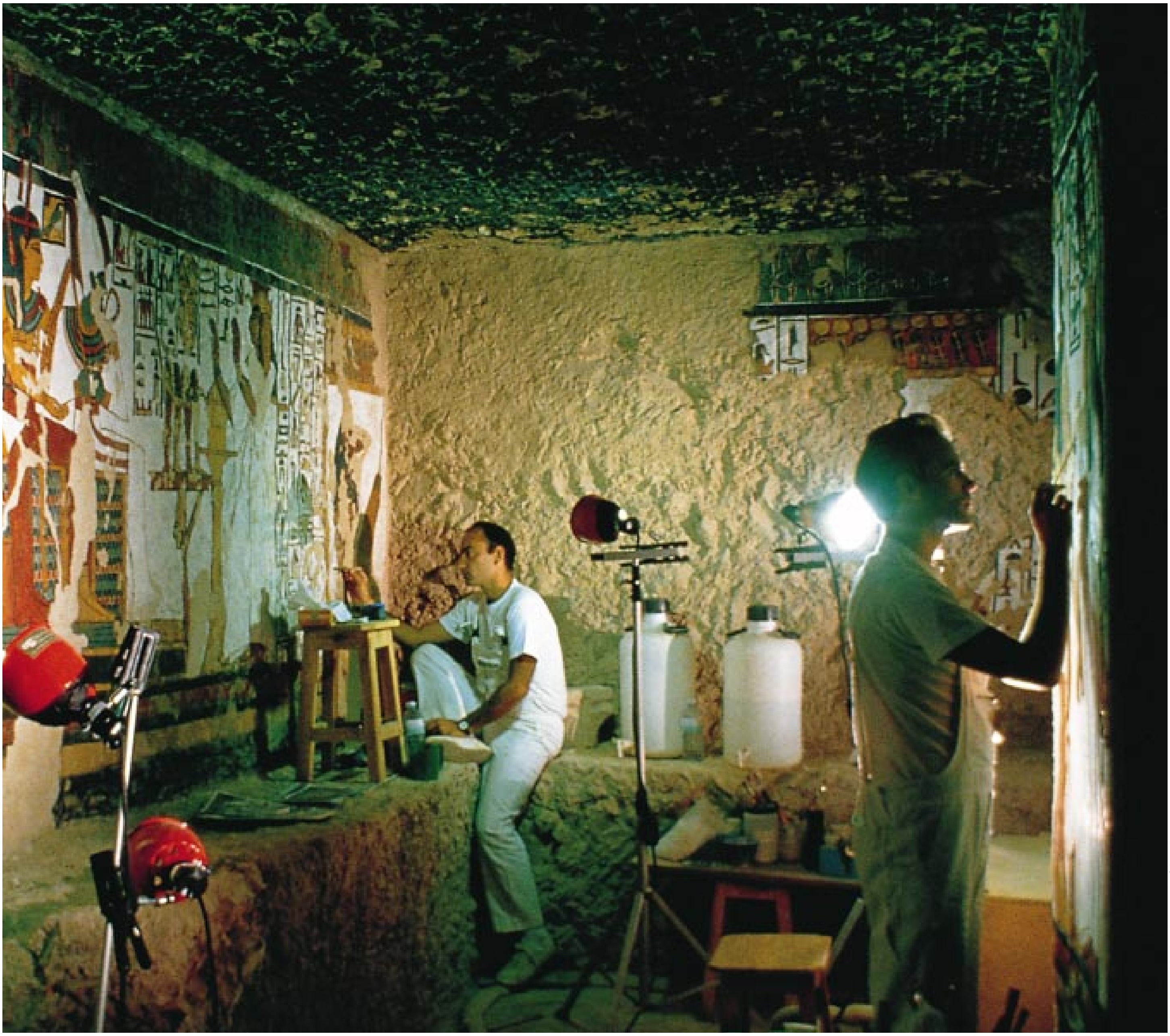
project combined the skills of art historians, conservationists, Egyptologists, environmental scientists, topographers, chemists, technicians and other specialists. It was not only a matter of protecting the wall paintings—a challenging enough task—but the microclimate and hydrological conditions of the entire tomb had to be understood and addressed so that the destruction would not start anew once the work was finished.

Now, seven years after completion, it is apparent that the paintings are stable and that the project is an enduring success. Visitors are once again able to see the marvelous images and to admire the serene beauty of Queen Nefertari. And they know they are looking at originals, not at the work of 20th-century hands. The team that labored on the undertaking agreed from the outset that no restoration would be done. In other words, no paint would be applied where it had been lost—despite the fact that the photographic records could have permitted such restoration.

The restoration of works of art is sometimes done, even if reluctantly, to re-create the original visual harmony and consistency of a piece. This process, however, inevitably compromises the integrity of the object. In the case of Nefertari's tomb—a site of great antiquity—everyone involved decided that the wall paintings should show evidence of the passage of time and that the ancient should not be hybridized with the modern.

Assessing the Damage

The team began the conservation process by evaluating the overall condition of the paintings. They studied every inch of plaster to see where it had fallen off, whether it was holding together or holding to the wall, and whether it had cracked; they also looked for places where rock fragments were jutting through the plaster. They examined the paint to



PHOTOGRAPHS BY G. ALDANA *J. Paul Getty Trust*

see whether it was flaking, being abraded or losing its cohesiveness and whether it was covered with dirt, dust or insect nests. At the same time, the team recorded the extent of the salt crystallization on the surface of the paintings and between the rock face and the plaster. Finally, they located the earlier interventions: the places where paintings had been retouched, holes patched, and facing—such as gauze or adhesive tape—applied.

Once the condition survey was finished, Paolo Mora, former chief conservator of the Central Institute of Restoration in Rome, and his wife, Laura Mora, began the laborious work of conserving the paintings. The Moras and their colleagues started by taking minute pigment samples from the paintings as well as samples of the plaster underneath. Because of sophisticated machines and techniques—including x-ray diffraction, x-ray fluorescence, polarizing light microscopy, and gas and liquid chromatography—the scientists needed only the tiniest of samples to determine the chemical composition of the materials. Once the ingredients were known, the researchers could figure out how best to save or stabilize the ancient paintings. In the interim, they prevented further degradation by applying strips of Japanese mulberry bark paper to the plaster, which kept it from falling off the walls and which could be easily removed once they were ready to begin work.

They discovered that the pigments were, not surprisingly, typical of Nefertari's time: Egyptian green; Egyptian blue (or cuprorivaite); red from iron oxide, with a trace of manganese and arsenic; ocher for yellow; calcite, anhydrite and huntite for white; and charcoal for black. The binding medium—which holds the pigments together—was largely gum arabic, a natural resin from a local acacia tree. The workers also found that some of the paintings had been varnished with tree resin and egg white—although two modern synthetic resins showed up as well in lab analyses, suggesting that there had been some earlier, undocumented restoration effort. The plaster was composed of gypsum, anhydrite and Nile silt, with some crushed limestone mixed in; wheat straw had been used to reinforce it and to prevent it from cracking as it dried.

Once they knew what they were dealing with, the team members could set about the work. For 469 days—spread over five years—they cleaned paintings, removed salt crystals from rock faces and in places underneath the plaster, and then reattached the plaster to the bedrock using an acrylic adhesive mixed with local sand and gypsum powder. They reattached flakes of paint and in places where the binding medium had degraded added a compound called acrylic copolymer to prevent it from breaking down further. They filled in holes with lime mortar and removed old, badly done repairs.

It was critically important that these efforts not affect the original colors. So before they even started any of this conservation work, Michael Schilling of the Getty Conservation Institute made 1,500 color measurements at 160 locations throughout the tomb. He used a chromometer (in this case, a Minolta CR-121) to assess exact hue. These records not only helped to guide the process by demonstrating that no shift in the color had occurred but also will aid ongoing monitoring of the paintings.

Keeping the Salt Out

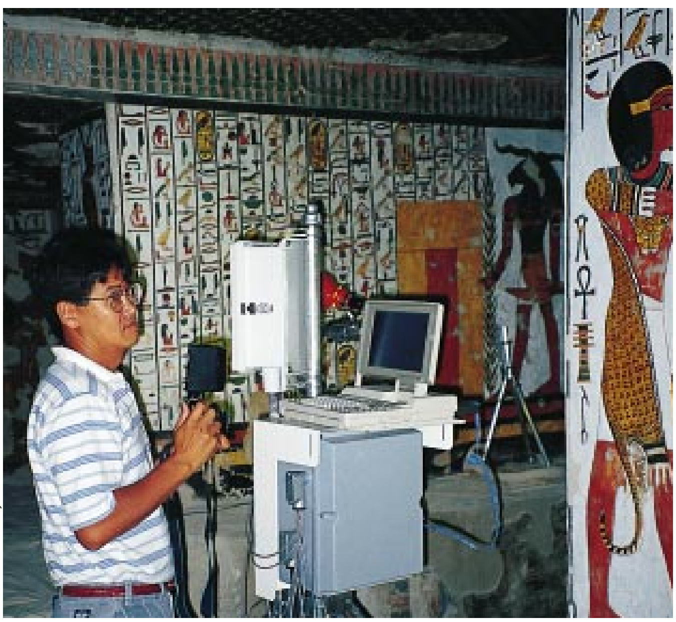
Concern about the future of these paintings centers on the most obvious threat: salt. When work began on the tomb, thick, 15-millimeter (0.6-inch) layers of salt were discovered under the plaster, forcing it from the wall. The salt came from Theban limestone, the marine sediment into which the tomb was cut. Salt is not a worry in most tombs, because the extremely dry Egyptian climate serves as a powerful preservative, keeping mummies and their artifacts sere and intact. But the site of Nefertari's tomb had some source of water that dissolved the salt and made it mobile.

Not everyone who has worked on the project agrees—even today, after years of study—about where exactly the water came from. Some was clearly introduced in the wet plaster applied by Ramses's wall painters themselves. That moisture, however, would not have caused thick layers of crystals to form. A more probable explanation is the very occasional, but very heavy, rain that falls about every 50 years on average. Many of the tombs in the region, including those in the Valley of the Kings, have flooded repeatedly since antiquity. Moisture infiltration is evident in Nefertari's tomb, especially at the entrance. It is likely that water seeped slowly through fissures, leaching salt from the bedrock as it traveled and leaving salt behind and on the painted surfaces as it evaporated from the walls.

To monitor humidity and temperature, one of us (Maekawa) recorded both the external climate and the microclimate of the tomb over several years and seasons. He found that the external temperature varied from a high of 40 degrees Celsius (104 degrees Fahrenheit) in the summer to 10 degrees C (50 degrees F) in the winter mornings; external humidity fluctuated wildly as well, from 80 percent in the winter to as low as 10 percent during the rest of the year. These outside conditions could affect the tomb because of leaks at the entrance, but for the most part, the internal temperature remained about 29 degrees C and humidity was stable at 50 percent. Maekawa also noted that there was natural ventilation during the winter: cooler air entered the tomb at floor level, forcing warmer air out through the entrance stairway. This movement caused the paintings and plaster to stay dry. When visitors entered the tomb, however, humidity rose sharply.

Maekawa had to take into account the fact that peak tourist season falls primarily during the summer—just when air is not circulating back outside and humidity could easily become trapped in the tomb. The more sweat and moisture in the tomb, the more likely it is that microflora, such as mold and bacteria, will grow on the surface of the paintings and destroy them and that salt crystals could begin to develop again.

In addition to monitoring temperature and humidity, Maeka-


NEVILLE AGNEW *Getty Conservation Institute*

ENVIRONMENTAL MONITORING is crucial to the future of the paintings. Shin Maekawa used a solar-powered system to study the microclimate of the tomb (*left*); he determined that the number of visitors had to be carefully regulated so that the temperature and humidity in the tomb did not catalyze the growth of salt crystals again. No more than 150 tourists are allowed in per day (*below*).


SHIN MAEKAWA *Getty Conservation Institute*

G. ALDANA *J. Paul Getty Trust*

WALL PAINTINGS are now fully conserved, and the images of Queen Nefertari's voyage to the afterlife remain vibrant. Their continued survival depends on striking a careful balance between public access and protection of the paintings.

wa had to carefully track levels of carbon dioxide. Because the tomb's natural ventilation is poor, this gas does not move out of the tomb easily and can pose a health hazard for tourists. Carbon dioxide can also react with moisture in the air, producing carbonic acid, which can discolor the wall paintings. Maekawa found that ambient levels of 340 parts per million (ppm) surged to 2,500 ppm when tourists visited the tomb. For health reasons, levels should not get higher than 1,000 ppm.

Keeping these findings in mind, the Egyptian Antiquities Organization—now the Supreme Council of Antiquities—designed a system that would ostensibly protect the tomb and yet would allow visitors to see it. They installed lights that gave off very little heat. And they set up a ventilation system that extracts air from the tomb, allowing unfiltered, dry air from the outside to flow in and replace the humid air generated by the visitors. Since late 1995 a maximum of 150 people a day, in groups of 10 to 15, have been allowed in for no more than 15 minutes. (They pay $30 for the visit, a fee that has generated about $1.5 million each year for the Egyptian government.) To date, the only noticeable impact of the stream of visitors has been an influx of dust, which has settled on the paintings, obscuring them somewhat.

Despite this careful monitoring, the potential damage of these visitors needs to be considered carefully and periodically evaluated. Although people should be free to see the beautiful paintings, to experience the mystery and awe of this gate to our past, we must establish a balance—a difficult task that extends far beyond Nefertari's tomb to all other threatened archaeological sites. Because damage is irreversible and cumulative—and because we seem to be able to destroy in just a few decades what has survived for millennia—it may not be right for everyone to have the access they expect. After all, that is what Ramses II intended for his wife: a peaceful, sealed existence.

The Authors

NEVILLE AGNEW and SHIN MAEKAWA work together at the Getty Conservation Institute in Los Angeles and have collaborated on archaeological projects all over the world. Agnew, who received his doctorate in chemistry, is group director for information and communications at the GCI. Maekawa, who specializes in environmental monitoring and the control of microenvironments, is a senior scientist at the institute. Maekawa developed the oxygen-free display cases for pharaonic mummies that are used in the Egyptian Museum in Cairo.

Further Reading

THE GREAT BELZONI: ARCHAEOLOGIST EXTRAORDINARY. Stanley Mayes. Walker, 1961.

ART AND ETERNITY: THE NEFERTARI WALL PAINTINGS CONSERVATION PROJECT 1986–1992. Edited by M. A. Corzo and M. Afshar. Getty Conservation Institute, Los Angeles, 1993.

DAILY LIFE IN ANCIENT EGYPT. Andrea G. McDowell in *Scientific American,* Vol. 275, No. 6, pages 100–105; December 1996.

HOUSE OF ETERNITY, THE TOMB OF NEFERTARI. John K. McDonald. J. Paul Getty Museum, Los Angeles, 1996.

The Unmet Challenges

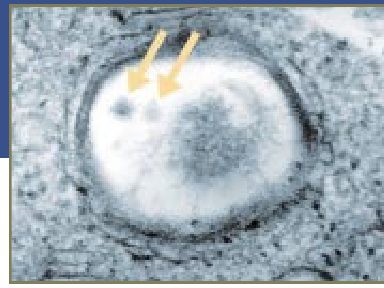
Some 1.8 percent of the U.S. adult population are infected with the hepatitis C virus, most without knowing it

by Adrian M. Di Bisceglie and Bruce R. Bacon

As recently as the late 1980s few people other than physicians had heard of hepatitis C, a slowly progressing viral infection that over a couple of decades can lead to liver failure or liver cancer. Today the condition is widely recognized as a huge public health concern. Some 1.8 percent of the U.S. adult population, almost four million people, are infected with the hepatitis C virus, most of them without knowing it. The virus is one of the major causes of chronic liver disease, probably accounting for even more cases than excessive alcohol use, and is the most common reason for liver transplants. Some 9,000 people die each year in the U.S. from complications of the infection, a number that is expected to triple by 2010. Information about the incidence of hepatitis C in other countries is less reliable, but it is clear that the virus is a major public health problem throughout the world.

Physicians, historians and military leaders have long recognized hepatitis—inflammation of the liver—as a cause of jaundice. This yellow discoloration of the whites of the eyes and skin occurs when the liver fails to excrete a pigment called bilirubin, which then accumu-

# of Hepatitis C



THE CULPRIT? Electron micrograph shows what is thought to be hepatitis C virus particles inside a cell vesicle.

lates in the body. In recent decades, however, the diagnosis of hepatitis has progressively improved, and physicians can now distinguish several distinct forms. At least five different viruses can cause the condition, as can drugs and toxins such as alcohol.

Researchers first studied viral hepatitis in the 1930s and 1940s in settings where jaundice was common, such as prisons and mental institutions. They identified two distinct forms with different patterns of transmission. One was transmitted by contact with feces of infected individuals and was called infectious hepatitis, or hepatitis A. The other appeared to be passed only through blood and was termed serum hepatitis, or hepatitis B.

An important development occurred in the 1950s, when researchers devised tests for liver injury based on certain enzymes in blood serum. When liver cells—known as hepatocytes—die, they release these enzymes into the circulation, where their concentrations can be easily measured. Elevated serum levels of alanine aminotransferase (ALT) and, especially, aspartate aminotransferase (AST) became recognized as more reliable signs of liver trouble than jaundice. (In addition to hepatitis, some uncommon inherited metabolic diseases can cause elevated liver enzymes.)

There things stood until Baruch Blumberg, working at the National Institutes of Health, made a breakthrough in the mid-1960s. Blumberg identified the signature of a viral agent, now known as hepatitis B virus, in the blood of patients with that disease. Blumberg's discovery won him a Nobel Prize and allowed researchers to develop reliable blood tests for the virus. A decade later Stephen M. Feinstone, a researcher at the same institution, identified a different viral agent in the stool of patients with hepatitis A. This work led quickly to the development of tests that accurately detect antibodies to hepatitis A virus in the blood of those infected.

Hepatitis had long been a significant risk for recipients of blood transfusions and blood products. As many as 30 percent of patients receiving a blood transfusion in the 1960s developed elevated levels of ALT and AST, or even jaundice, some weeks later. Workers had suspected an infectious agent was responsible. When the new tests for hepatitis A and B became available in the 1970s, researchers soon found that a substantial proportion of cases of post-transfusion hepatitis were caused by neither of these two viruses. The new disease was labeled "non-A, non-B" hepatitis.

Most investigators expected that the agent responsible for these cases would soon be discovered. In reality, it took nearly 15 years before Michael Houghton and his colleagues at Chiron Corporation, a biotechnology company in Emeryville, Calif., finally identified the hepatitis C virus, using samples of serum from infected chimpanzees provided by Daniel W. Bradley of the Centers for Disease Control and Prevention. Hepatitis C accounts for most cases of viral hepatitis that are not types A or B, although a few result from other, rarer viruses.

The Needle in an RNA Haystack

Hepatitis C virus proved difficult to identify because it cannot be reliably grown in cell cultures, and chimpanzees and tamarins appear to be the only nonhuman animals that can be infected. Because both species are very expensive to use in research, only small numbers of animals can be employed. These obstacles, which still impede the study of the virus, explain why it was the first infectious agent discovered entirely by cloning nucleic acid.

The Chiron researchers first extracted RNA from serum samples strongly suspected to contain the unknown viral agent. A chemical variant of DNA, RNA is used by many viruses as their genetic material. RNA is also found in healthy cells, so the problem was to identify the tiny fraction corresponding to the unknown viral genome.

The Chiron workers used an enzyme to copy multiple fragments of DNA from the RNA, so that each carried some part of its genetic sequence. Next, they inserted this "complementary DNA" into viruslike entities that infect *Escherichia coli* bacteria, which induced some bacteria to manufacture protein fragments that the DNA encoded. The researchers grew the bacteria to form colonies, or clones, that were then tested for their ability to cause a visible reaction with serum from chimpanzees and a human with non-A, non-B hepatitis.

The hope was that antibodies in the serum would bind to any clones producing protein from the infectious agent. Out of a million bacterial clones tested, just one was found that reacted with serum from chimpanzees with the disease but not with serum from the same chimpanzees before they had been infected. The result indicated that this clone contained genetic sequences of the disease agent. Using the clone as a toehold, investigators subsequently characterized the remainder of the virus's genetic material and developed the first diagnostic assay, a test that detects antibodies to hepatitis C in blood. Since 1990 that test and subsequent versions have allowed authorities to screen all blood donated to blood banks for signs of infection.

The antibody test soon showed hepatitis C to be a much bigger threat to public health than had generally been recognized. A remarkable feature—one that sets it apart from most other viruses—is its propensity to cause chronic disease. Most other viruses are self-limited: infection with hepatitis A, for example, usually lasts for only a few weeks. In contrast, nearly 90 percent of people with hepatitis C have it for years or decades.

Few patients know the source of their virus, but on direct questioning many recall having a blood transfusion, an episode of injection drug use or an injury from a hypodermic needle containing blood from an infected individual. About 40 percent of patients have none of these clear risk factors but fall into one of several categories identified in epidemiologic studies. These include having had sexual contact with someone with hepatitis, having had more than one sexual partner in the past year, and being of low socioeconomic status.

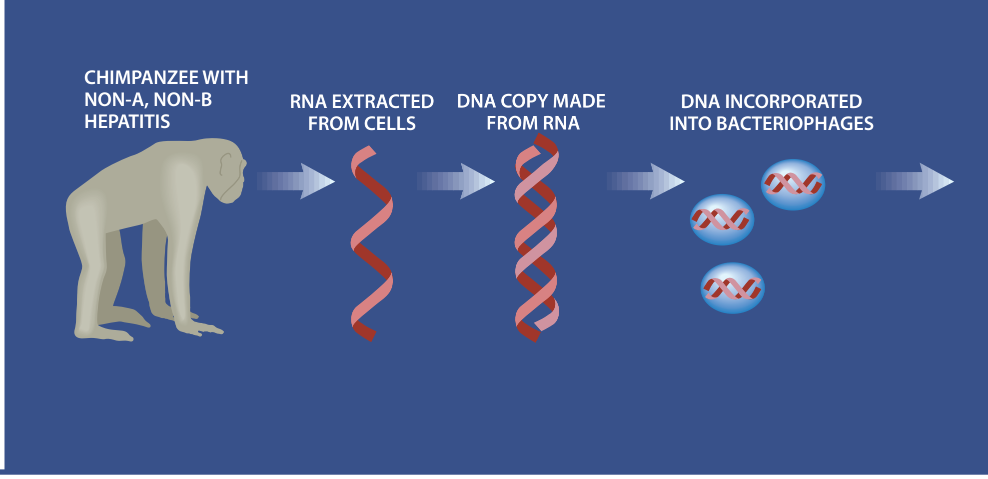
Whether hepatitis C is sexually trans-

PHOTOGRAPH BY TONY STONE IMAGES; PHOTOMANIPULATION BY JANA BRENNING *(opposite page)*; YOHKO K. SHIMIZU *National Institutes of Health (inset)*

How the Hepatitis C Virus Was Discovered

Researchers identified the hepatitis C virus by making DNA copies of RNA from the cells of infected chimpanzees. They cloned the DNA by using bacteriophages to carry it into bacteria. Colonies were then tested with serum from infected chimps. One produced an immune reaction, indicating it carried viral genetic sequences. *—A.M.D. and B.R.B.*

LAURIE GRACE



mitted is controversial. Instances of transmission between partners in stable, monogamous relationships are rarely identified, and the rate of infection in promiscuous gay men is no higher than in the population in general. These observations suggest that sexual transmission is uncommon, but they are hard to reconcile with the epidemiologic findings. The paradox has not been resolved. Some patients who deny injection drug use may be unwilling or unable to recall it. Others might have been infected from unsterile razors or tattooing instruments. Shared straws put into the nose and used to snort street drugs might also transmit the virus via minute amounts of blood.

Slow Progress

The discovery of hepatitis C virus and the development of an accurate test for it mark an important victory for public health. The formerly substantial risk of infection from a blood transfusion has been virtually eliminated. Moreover, the rate of infection appears to be dropping among injection drug users, although this may be because anti-AIDS campaigns have discouraged sharing of needles. Yet hepatitis C still presents numerous challenges, and the prospects for eradicating the virus altogether appear dismal. Attempts to develop a vaccine have been hampered because even animals that successfully clear the virus from their bodies acquire no immunity to subsequent infection. Moreover, millions of people who are chronically infected are at risk of developing severe liver disease.

The mechanism of damage is known in outline. Viral infections can cause injury either because the virus kills cells directly or because the immune system attacks infected cells. Hepatitis C virus causes disease through the second mechanism. The immune system has two operating divisions. The humoral arm, which is responsible for producing antibodies, appears to be largely ineffective against hepatitis C virus. Although it produces antibodies to various viral components, the antibodies fail to neutralize the invader, and their presence does not indicate immunity, as is the case with hepatitis B.

It seems likely that hepatitis C virus evades this defense through its high mutation rate, particularly in regions of its genome responsible for the manufacture of proteins on the outside of the virus to which antibodies might bind. Two such hypervariable regions have been identified within the so-called envelope regions of the genome. As many as six distinct genotypes and many more subtypes of the virus have been identified; numerous variants exist even within a single patient.

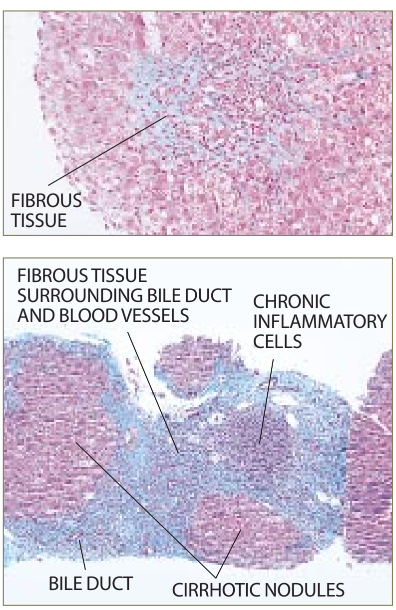
In contrast to the humoral arm, the cellular arm of the immune system, which specializes in viral infections, mounts a vigorous defense against hepatitis C. It appears to be responsible for most of the liver injury. Cytotoxic T lymphocytes primed to recognize hepatitis C proteins are found in the circulation and in the liver of chronically infected individuals and are thought to kill hepatocytes that display viral proteins. Fortunately, liver tissue can regenerate well, but that from hepatitis patients often contains numerous dead or dying hepatocytes, as well as chronic inflammatory cells such as lymphocytes and monocytes.

Long-Term Consequences

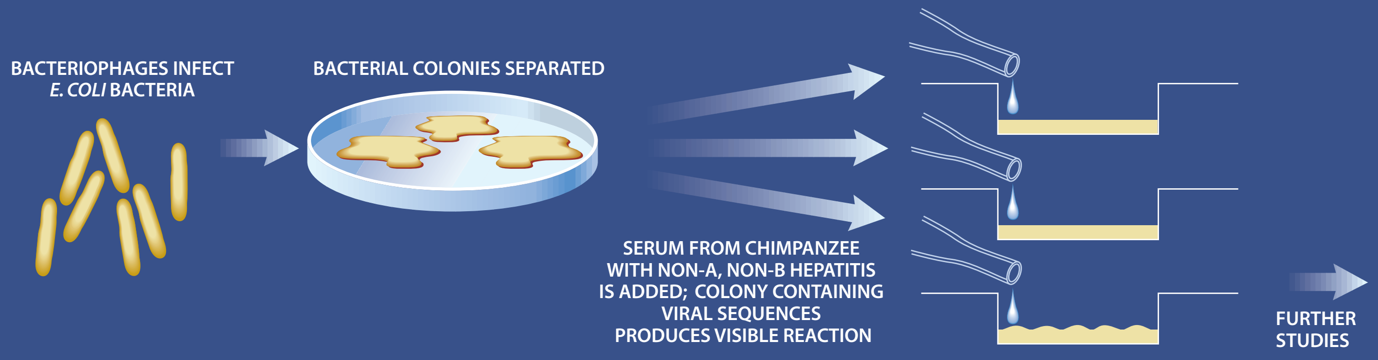
If hepatitis persists for long enough—typically some years—the condition escalates, and normally quiescent cells adjacent to hepatocytes, called hepatic stellate cells, become abnormally activated. These cells then secrete collagen and other proteins, which disrupt the fine-scale structure of the liver and slowly impair its ability to process materials. This pathology is known as fibrosis. Stellate cells are similar in origin and function to the fibrosis-producing cells found in other organs, such as fibroblasts in the skin and mesangial cells in the kidney. They store vitamin A as well as produce the liver's extracellular matrix, or framework. It is likely that many of the processes that initiate the fibrotic response in the liver occur in these other tissues as well.

If fibrosis progresses far enough, it results in cirrhosis, which is characterized by bands of fibrosis enclosing nodules of regenerating hepatocytes. Progression is

ELIZABETH M. BRUNT *Saint Louis University*



LIVER TISSUE from patients with hepatitis C often shows fibrosis—excess collagen (*here stained blue*). The top image shows typical mild fibrosis. The bottom image shows cirrhosis, a more serious condition in which fibrotic tissue surrounds regenerating nodules of hepatocytes; chronic inflammatory cells are also visible.



faster in people over age 50 at the time of infection, in those who consume more than 50 grams of alcohol a day, and in men, but cirrhosis can result even in patients who never drink alcohol. Fibrosis and cirrhosis are generally considered irreversible, although recent findings cast some doubt on that conclusion.

About 20 percent of patients develop cirrhosis over the first 20 years of infection. Thereafter some individuals may reach a state of equilibrium without further liver damage, whereas others may continue to experience very slow but progressive fibrosis. End-stage liver disease often manifests itself as jaundice, ascites (accumulation of fluid within the abdomen), bleeding from varicose veins within the esophagus, and confusion. Hepatitis C infection has also come to be recognized as a major indirect cause of primary liver cancer. The virus itself seems not to put people at increased risk, but cirrhosis induced by the virus does.

Cirrhosis is responsible for almost all the illness caused by the hepatitis C virus. Although a small proportion of patients recollect an episode of jaundice when they probably acquired their infection, chronic hepatitis C is often asymptomatic. When symptoms do occur, they are nonspecific: patients sometimes complain of vague feelings of fatigue, nausea or general unwellness. The insidious nature of the condition is probably another reason why hepatitis C remained undiscovered for as long as it did. The disease plays out over decades. An aspect confounding investigators is that not all infected individuals react in the same way. Some may carry the virus for decades without significant injury; others experience serious damage within only a few years.

Liver transplantation can save some end-stage patients, but the supply of human livers available for transplant is woefully inadequate. Researchers are therefore working intensively to develop treatments that will eradicate the virus in patients.

The first therapeutic agent shown to be effective was alpha interferon, a protein that occurs naturally in the body. Interferon appears to have a nonspecific antiviral action and may also enhance immune system activity. The drug is generally given by subcutaneous injection three times a week for 12 months. Only 15 to 20 percent of patients, however, exhibit a sustained response, as defined by the return of ALT and AST to normal levels and the absence of detectable hepatitis C RNA in serum for at least six months after stopping treatment. Why treatment fails in most patients is essentially unknown, although some viral genotypes seem to be more susceptible to interferon than others.

Last year the Food and Drug Administration approved another drug, ribavirin, to treat hepatitis C in conjunction with interferon. Ribavirin, which can be swallowed in pill form, inhibits many viruses. Interestingly, though, it appears to have no effect against the hepatitis C virus by itself and is thought somehow to enhance interferon's effects on the immune system. Interferon and ribavirin given together for six to 12 months can expunge the virus in about 40 percent of patients, and clinical workers are now studying how to maximize the benefits from these two agents. Long-acting forms of interferon that require administration only once a week are one focus of interest.

A new drug is now being tested in small numbers of patients. Vertex Pharmaceuticals in Cambridge, Mass., is investigating a compound that inhibits a human enzyme called ionosine monophosphate dehydrogenase. The hepatitis C virus relies on this enzyme to generate constituents of RNA. No results from these trials are yet available.

In the absence of medications capable of dependably eliminating the virus, the NIH recently embarked on a study to determine whether long-term administration of alpha interferon can slow liver damage in patients who fail to clear the virus. And we and other researchers are studying the simple expedient of taking a pint of blood from patients on a regular basis. This treatment reduces the amount of iron in the body, a manipulation that can reduce serum ALT and AST levels. Whether it slows liver damage is still uncertain.

Targeting the Virus

The best prospects for future treatment for hepatitis C appear to be agents targeted specifically against the virus, just as successful treatments for HIV target that agent. With that goal in mind, researchers have elucidated the structure of the hepatitis C virus in detail. Its genetic material, or genome, consists of a single strand of RNA. In size and organization the genome is similar to that of yellow fever and dengue fever viruses; hepatitis C virus has therefore been classified with them as a member of the family Flaviviridae. Enzymes in an infected cell use the viral RNA as a template to produce a single large protein called a polyprotein, which then cleaves to yield a variety of separate proteins with different functions. Some are structural proteins that go to form new viral particles; others are enzymes that replicate the original infecting RNA. At either end of the genome are short stretches of RNA that are not translated into protein. One of these terminal regions seems to prompt infected cells to manufacture the viral polyprotein; it is an important target for diagnostic assays. The other appears to play a role in initiating the replication of viral RNA.

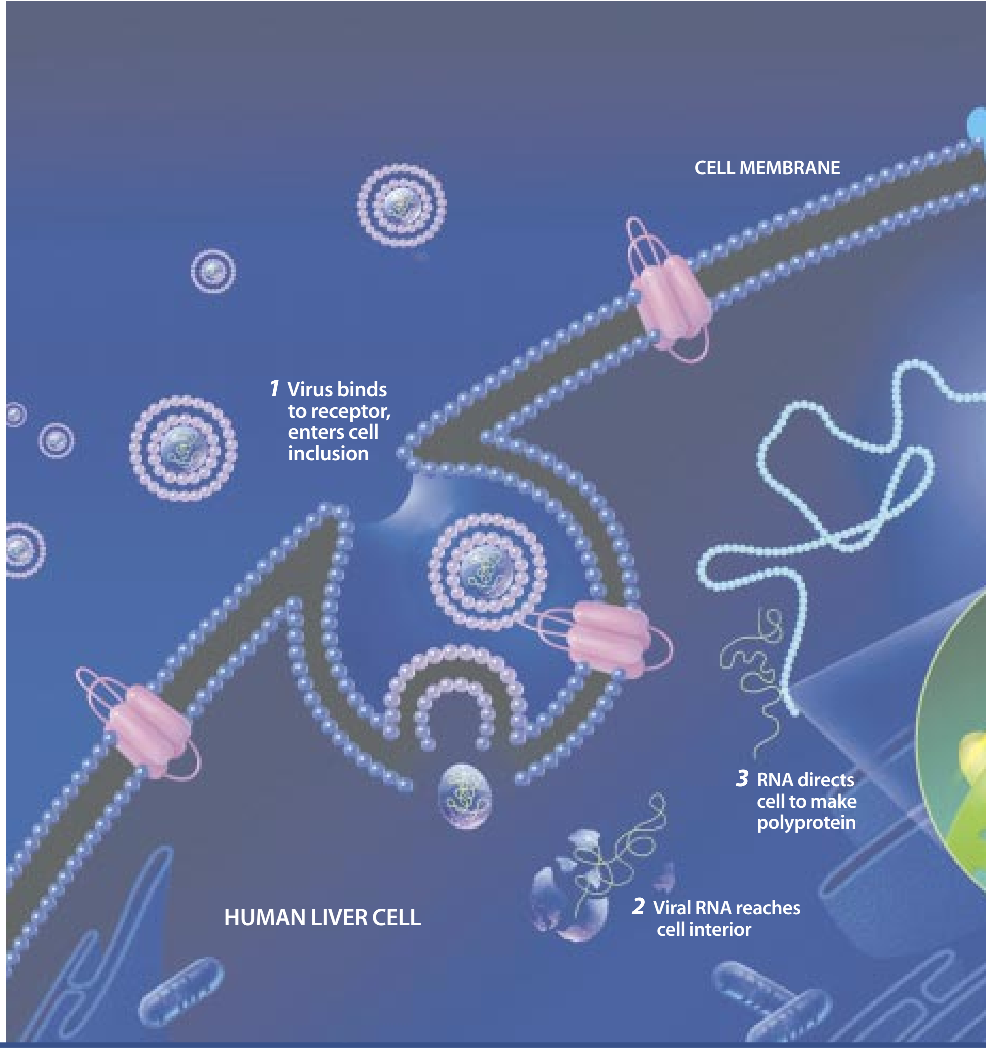
The structural proteins include the

How the Hepatitis C Virus Reproduces Itself

Hepatitis C infection starts when viral particles in the circulation find their way to susceptible cells, particularly hepatocytes. A viral protein called E2 appears to facilitate entry by latching onto a specific receptor. On entering, the virus loses its lipid coat and its protein envelope, freeing the RNA cargo. Enzymes in the cell then use this RNA as a template to make a large viral protein, the polyprotein. It is cleaved into a variety of small proteins that go on to form new viral particles and help to copy the viral RNA.

The original RNA is copied to yield a "negative-stranded" RNA that carries the inverse, or complement, of the original sequence. This serves as a template to make multiple copies of the original RNA, which are incorporated into new viral particles, along with structural proteins, at a body called the Golgi complex. Complete viral particles are eventually released from the infected cell, after acquiring a lipid surface layer. Recent studies suggest that a patient produces as many as 1,000 billion copies of hepatitis C virus a day, most of them from the liver. *—A.M.D. and B.R.B.*

KEITH KASNOT; SOURCE: CHARLES M. RICE *Washington University School of Medicine*



core protein, which encloses the RNA in a viral particle within a structure known as the nucleocapsid, and two envelope proteins that coat the nucleocapsid. The nonstructural proteins include a viral protease responsible for cleaving the polyprotein, as well as other enzymes responsible for chemically readying the components of viral RNA (triphosphatase), for copying the RNA (polymerase) and for unwinding the newly manufactured copy (helicase).

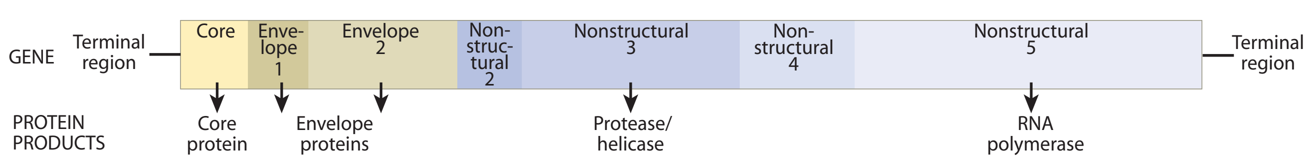
The protease and helicase enzymes have been well characterized and their detailed three-dimensional structure elucidated through x-ray crystallography, necessary first steps for designing drugs to inhibit an enzyme. Several drug companies, including Schering-Plough, Agouron Pharmaceuticals, and Eli Lilly and Vertex Pharmaceuticals, are now studying potential hepatitis C protease or helicase inhibitors. Clinical trials are probably only a few years away. Another viral enzyme, the polymerase, is also a possible target. Whether the virus will evolve resistance to such agents remains to be seen.

Developing anti–hepatitis C therapies may be about to get easier. Three months ago Ralf Bartenschlager and his colleagues at Johannes-Gutenberg University in Mainz, Germany, published details of an RNA genetic construct that includes the regions coding for the virus's enzymes and reproduces itself in liver cancer cell lines. This construct may prove valuable for testing drugs targeted at these enzymes.

Another possible therapeutic avenue being investigated is disruption of the process that activates hepatic stellate cells and causes them to instigate fibrosis. This mechanism is known to involve cytokines, or signaling chemicals, that cells in the liver called Kupffer cells release when they are stimulated by lymphocytes. Turning this process off once it has started should prevent most of the untoward consequences of hepatitis C infection.

Some workers are trying to develop therapeutics aimed at the short terminal regions of the virus's genome. One idea,

HEPATITIS C VIRUS GENOME consists of a single RNA gene plus two terminal regions. The gene encodes a polyprotein, which subsequently cleaves to form a variety of smaller proteins. Some of these are used to make new virus particles; others are enzymes that help to replicate the viral RNA for inclusion into new viruses.



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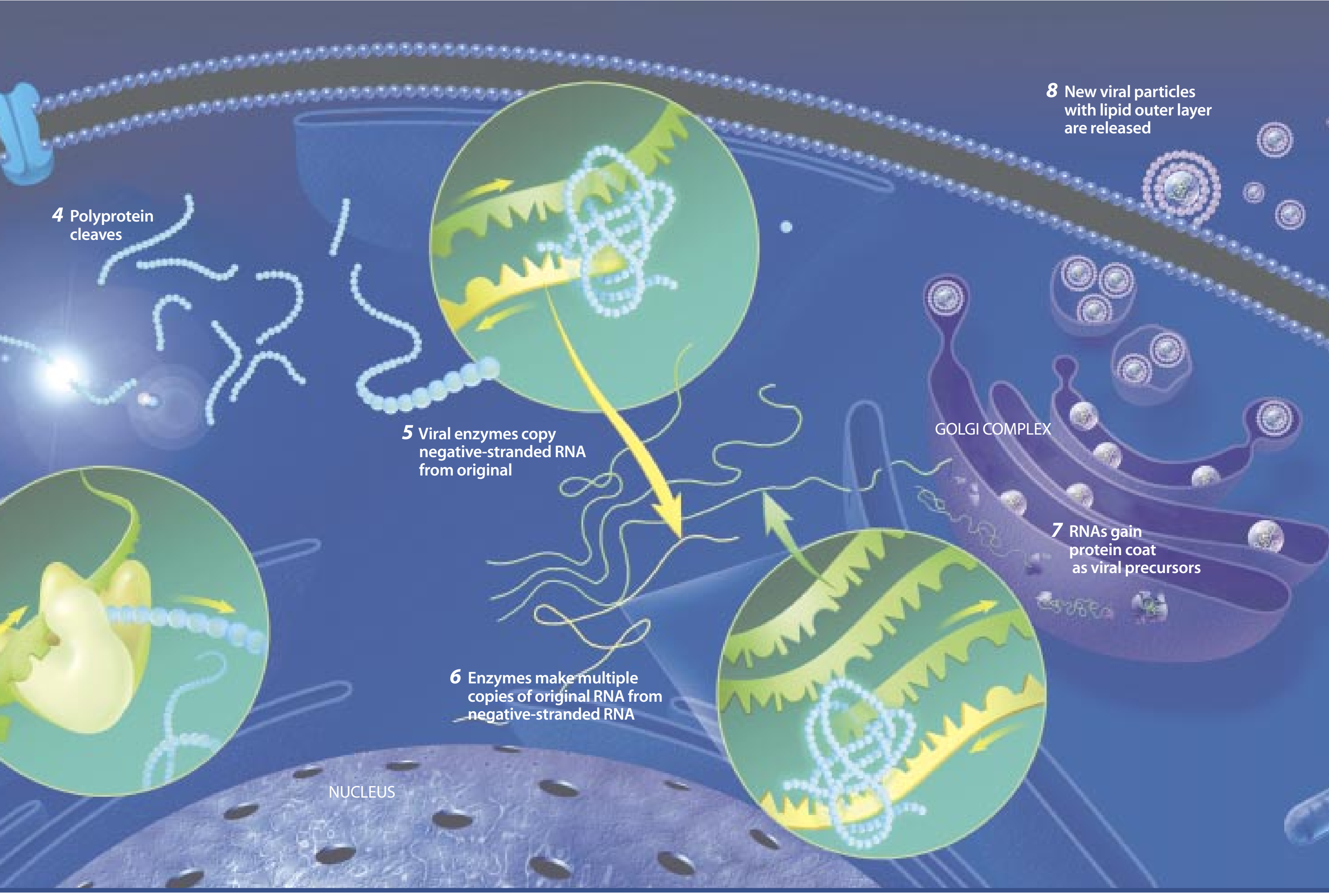

being pursued by Ribozyme Pharmaceuticals, is to develop therapeutic molecules that can cut specific constant sequences there. Ribozymes, short lengths of RNA or a chemical close relative, can accomplish this feat. The main challenge may be getting enough ribozymes into infected cells. Delivering adequate quantities of a therapeutic agent is also a problem for some other innovative treatment concepts, such as gene therapy to make liver cells resistant to infection, "antisense" RNA that can inhibit specified genes, and engineered proteins that activate a cell's self-destruct mechanism when they are cleaved by the hepatitis C protease.

All these attempts to counter hepatitis C are hampered by a serious shortage of funds for research. The amount of federal support, considering the threat to millions of patients, is relatively small. We are confident that much improved therapies, and possibly a vaccine, will in time be available. An expanded research program could ensure that these developments come soon enough to help patients and those at risk. SA

The Authors

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Further Reading

THE CRYSTAL STRUCTURE OF HEPATITIS C VIRUS NS3 PROTEINASE REVEALS A TRYPSIN-LIKE FOLD AND A STRUCTURAL ZINC BINDING SITE. Robert A. Love et al. in *Cell*, Vol. 87, No. 2, pages 331–342; October 18, 1996.

MANAGEMENT OF HEPATITIS C. National Institutes of Health Consensus Development Conference Panel Statement. In *Hepatology*, Vol. 26, Supplement No. 1, pages 2S–10S; 1997.

INTERFERON ALFA-2B ALONE OR IN COMBINATION WITH RIBAVIRIN AS INITIAL TREATMENT FOR CHRONIC HEPATITIS C. John G. McHutchison et al. in *New England Journal of Medicine*, Vol. 339, No. 21, pages 1485–1492; November 19, 1998.

MOLECULAR CHARACTERIZATION OF HEPATITIS C VIRUS. Second edition. Karen E. Reed and Charles M. Rice in *Hepatitis C Virus*. Edited by H. W. Reesink. Karger, Basel, 1998.

REPLICATION OF SUBGENOMIC HEPATITIS C VIRUS RNAS IN A HEPATOMA CELL LINE. V. Lohmann, F. Körner, J.-O. Koch, U. Herian, L. Theilmann and R. Bartenschlager in *Science*, Vol. 285, pages 110–113; July 2, 1999.

The largely mythical decline of science in the public schools is leading—yet again—to rushed reforms that ignore the best advice on what kids should *know*

STUDENTS in an 11th-grade chemistry laboratory class.

The False Crisis in Science Education

by W. Wayt Gibbs and Douglas Fox

On a cold and rainy day this past February, Bruce Alberts wore a grim expression as he stepped up to the microphones at the National Press Club in Washington, D.C. The final results of the Third International Mathematics and Science Study (TIMSS) had just come in, and America's high school seniors had placed near last.

"There is no excuse for this," President Bill Clinton had already chided. "These results are entirely unacceptable," admonished the secretary of education. The head of the National Education Association declared U.S. schools to be in a state of crisis. And now Alberts, president of the National Academy of Sciences, said that he, too, saw in this report "all the elements of an education tragedy."

"Americans have always risen to a crisis," he added. "We see clearly that the future is threatened. Let us act now to heed this important wake-up call." And so, with editorial writers and educators across the country obligingly sounding the alarm, American education lurched yet again into crisis mode.

It is a cyclical ritual, repeated in every decade since the 1940s, observes Gregory J. Cizek of the University of Toledo. The launch of Sputnik in 1957 set off an orgy of anxiety, culminating in Admiral Hyman Rickover's 1963 book *American Education: A National Failure,* in which he famously predicted that "the Russians will bury us" thanks to their more rigorous science and math courses. Beginning with the 1983 publication of *A Nation at Risk,* one blue-ribbon panel after another warned that massive educational failure had ceded the U.S.'s technological lead to Japan and other competitors—a conclusion that proved premature.

Although the particulars vary from one education crisis to the next, common threads connect these episodes. Each event has surged into public discourse on an unrelenting torrent of angst flowing from the educational research profession, Cizek says. Combing through the education literature of the past 30 years, he recently turned up more than 4,000 articles and books in which scholars declared some sort of crisis in the schools—but rarely bothered to spell out what cataclysm was imminent. Each episode has also eaten away at public confidence in schools, which fell 38 percent from 1973 to 1996, according to surveys by the National Opinion Research Center.

Most important, the crises all share a central logic. U.S. economic and scientific dominance is on the verge of collapsing because the schools are not producing enough scientists, engineers and other technically skilled workers. The schools crisis thus jeopardizes the nation's ability to compete in the global economy and to raise U.S. standards of living.

Cizek urges, however, that "we ought to be more skeptical of claims of crisis," and other educational historians agree. Despite researchers' fondness for this recurrent political phenomenon and the infusions of cash that it brings, there are three reasons to doubt its usefulness. One is that past crises have led to lots of spending and legislation—Paul DeHart Hurd of Stanford University counts nearly 1,000 laws passed since the 1970s to force reforms on schools—but have made little change in what students learn. In a crisis, Hurd observes, politicians tend to launch big reforms based on shaky evidence.

California, for example, spent $3.7 billion to reduce class sizes after Tennessee had rapid success in a small trial. After three years, student scores have barely budged. Yet the federal government has budgeted $12.4 billion to shrink classes.

A second reason for skepticism is that a close look at the statistical evidence reveals no sudden decline in the science and math knowledge of those leaving high school. To the contrary, teenagers' scores on national tests have been inching upward for more than a decade, and surveys show that the average young adult knows slightly more basic science than his parents and grandparents do [*see box on next page*].

From 1980 to 1995 college enrollments swelled 29 percent, despite a falling population of college-age kids—a decline, incidentally, that will reverse next year. Teachers boasted twice as many master's degrees and years of experience in 1996 as those in 1966 did. High school student–teacher ratios shrank 27 percent in the same period. This decade has seen the number of college degrees awarded in science and engineering soar.

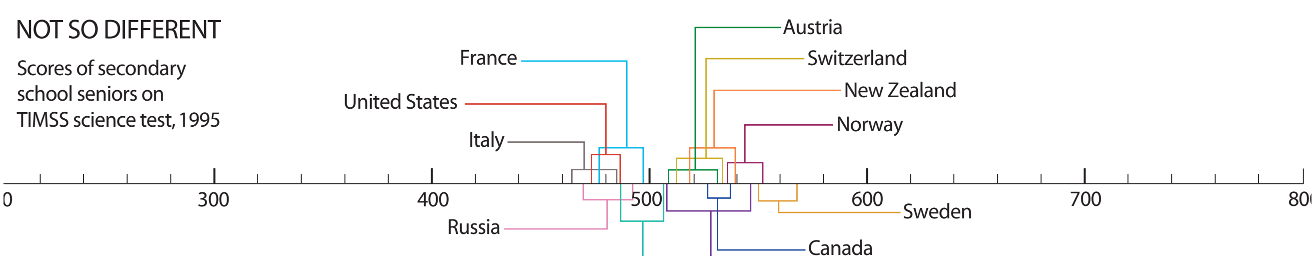


PHOTO RESEARCHERS, INC.

SARAH DONELSON

LOW RANK OF AMERICAN TEENAGERS on TIMSS made headlines, but that crude statistic belies how closely the average scores of the U.S.'s major competitors were clustered, especially when margins of error (*brackets*) are taken into account.

What then of American teenagers' disappointing showing in TIMSS, a four-year, 40-country, 500,000-student study that even critics such as education consultant Gerald Bracey grant is the "largest and best controlled methodologically" of all such tests? Some, such as Iris C. Rotberg of the Institute for Educational Policy Studies at George Washington University, have argued that it is unfair to compare U.S. students with those in countries that require more years of school or more science courses. Bracey similarly complains that in several of the high-scoring nations, secondary school seniors are older and much less likely to hold jobs than American kids are.

William H. Schmidt, who coordinated the U.S. arm of TIMSS, counters that these criticisms entirely miss the point of doing an international study, which is to clarify how different ways of running schools affect what students learn. After all, he points out, the U.S. could extend the age of compulsory schooling and give students stipends (as Sweden does) so that fewer need work, if those policies seem to be prerequisites for success.

In fact, TIMSS shows, they are not. Much more informative than the study's national rankings are its clues that ideas sometimes touted as necessary or sufficient for good schools are neither. Among many of the high-scoring nations, for example, students typically get less homework than their American peers and often attend larger classes. They spend no more, and sometimes less, classroom time on math and science. Few divide students into slow and fast tracks. Most make less use of technology than schools in the U.S. do.

Textbooks, however, do seem to matter. TIMSS researchers analyzed some 800 of the math and science texts most commonly used in the participating countries. With few exceptions, American texts covered many more topics than the foreign books and covered them over and over and over. "U.S. students make very small gains from fourth to eighth grade in all the areas tested, but large gains in none," Schmidt says. "High school simply continues the trend."

Thus, American teenagers score a bit lower than many peers overseas on a battery of mostly multiple-choice questions emphasizing basic facts and procedures. So what? "I am not convinced that a high score on TIMSS is equivalent to being scientifically literate," says Angelo Collins, who led the development of the National Science Education Standards. "The tests don't get at long-term problem-solving skills and concepts about the nature of science," agrees J. Myron Atkin of Stanford. "Trying to raise TIMSS scores is a regressive step, because those tests don't correspond to what we want our kids to know."

In an education crisis, the question of what schools *ought* to teach about science and math gets overlooked in a rush to raise test scores. That is the third reason to doubt that howls of crisis are helpful. A consensus has begun to emerge among science education researchers, teachers and practicing scientists that schools should turn out scientifically literate citizens, not more candidates for the academic elite.

Throughout U.S. history, Hurd maintains, precollege science courses have served as screens to filter out all but the brightest and most motivated students. "If you are good at memorizing jargon and formulas, you move on," Atkin

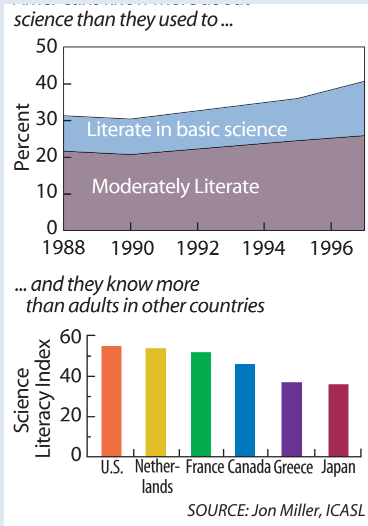
Continued on page 92

Dumb but not Dumber

In spite of the doom-and-gloom rhetoric popular among science educators, what scant data there are indicate that Americans are getting better at science, not worse. Biennial surveys conducted by Jon Miller of the International Center for the Advancement of Science Literacy in Chicago reveal that science literacy has increased among U.S. adults since 1985 (*upper chart*) and that 18- to 29-year-olds perform slightly better on the surveys than those older than 40 do. The scores of 17-year-olds on the National Assessment of Educational Progress in science and math have also risen slowly since 1982, although they are still below record highs set in the late 1960s.

The fact that U.S. 12th graders fall behind on international tests does not mean that Americans know less about science than adults in other nations do. In fact, U.S. residents have consistently demonstrated a firmer grasp of basic science facts than have denizens of many countries that dramatically outperformed the U.S. on TIMSS (*lower chart*). Miller attributes the good showing of the U.S. to its college attendance rates, which are higher than those elsewhere. College students in the U.S. are also more likely than their international counterparts to take general science courses.

Americans have no reason to gloat, however. U.S. adults may know more middle school science than most of the world, but they are shockingly ignorant nonetheless—most, for example, cannot recall the definition of a year (*below*). —*D.F.*



SOURCE: Jon Miller, ICASL

SARAH DONELSON

QUESTIONS FROM THE SCIENCE LITERACY SURVEY:

1. What is a molecule? (11 percent answered correctly)
2. What is DNA? (22 percent)
3. Do lasers work by focusing sound waves? (39 percent)
4. How long does it take the earth to circle the sun? (48 percent)

OVERSTUFFED U.S. texts cover many topics repeatedly but few at great depth.

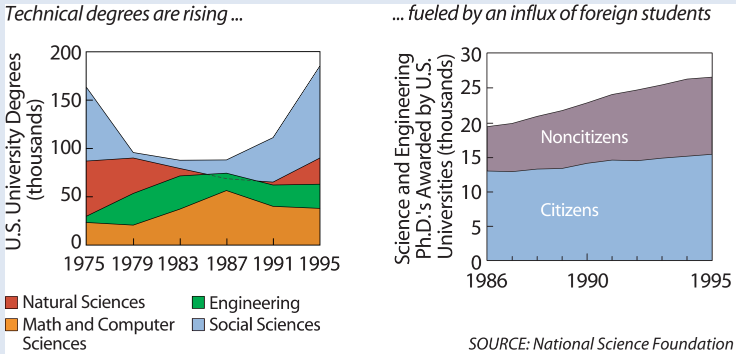
STEVE STARR *SABA*; ROBBIE McCLARAN *SABA*; JOHAN GUNSEUS *Pressens Bild/SABA*

U.S. Research Feels No Crisis

Whatever the state of secondary school math and science education, the university departments that produce the elite corps of scientists and engineers for the U.S. suffer no shortage of bright students (*left*). Annual production of science and engineering Ph.D.'s has soared 130 percent since 1966, while the U.S. population grew just 35 percent. Some disciplines have done better than others, of course—enrollment in physics Ph.D. programs is down 27 percent since 1992. But Patrick J. Mulvey of the American Institute of Physics claims that the dip merely reflects a sagging post–cold war job market for defense-related disciplines.

In other fields, forecasters worry more about a flood of new scientists than about a shortage of them. Last year a National Research Council report urged universities to freeze the size of their biology graduate programs for this very reason.

Part of the growth in U.S. Ph.D. production stems from a steady rise in international students (*right*). After graduating, a large fraction of these Ph.D. recipients have traditionally remained in the U.S. to work, and that proportion is growing. In 1996 about 68 percent of foreign citizens who received science or engineering doctorates planned to stay in the U.S., up from 49 percent in 1980. —*D.F.*



SOURCE: National Science Foundation

SARAH DONELSON

Wanted: Strong Thinkers

"When the economy is bad, schools always get the blame," observes J. Myron Atkin of Stanford University. "But when the economy is good, they never get the credit."

Atkin has a point. Two independent analyses of global economic competitiveness this year ranked the U.S. in first or second place (behind tiny Singapore). And yet a co-author of one of those reports, Harvard University economist Michael E. Porter, warned at a press conference in July that "although the U.S. is very competitive and pumping out innovations at a feverish pace today, the scientists that are creating those innovations graduated from university five to 20 years ago."

"Among the drivers of innovation," Porter concluded, "the biggest problem in the U.S. is a growing crisis in science and technical personnel." He and Harvard colleague Jeffrey Sachs called out the nation's public schools as a prime suspect.

Many take it as axiomatic that the science and math skills of high school graduates are critical to the health of the U.S. economy. But several lines of evidence contradict that assumption. To start, the detailed microeconomic analyses by Porter and others on which the competitiveness reports are based list dozens of variables, from trade policy to the zeal of antitrust prosecutors, that influence a nation's ability to succeed in the global economy. "Adequacy of schooling" is low on the list—beneath "port infrastructure quality," for example. "Quality of scientists and engineers" falls even lower. Both are among the hardest for politicians to change.

Furthermore, Porter's alarm notwithstanding, university production of scientists and engineers has been increasing overall [*see box above*], despite competition from a strong job market and a collapsing population of 20- to 24-year-olds. No one can predict whether recent graduates will be as productive as their predecessors. But it is interesting that many innovators who left university "five to 20 years ago" were schooled during the science education "crisis" of the early 1980s.

Anthony P. Carnevale, a labor economist with the Educational Testing Service in Princeton, N.J., raises a third point. "Just because technology is the major ingredient in the economic pie doesn't mean the pie then slices up into technology jobs," he says. Around the last turn of the century, new technologies based on electricity, aluminum, automobiles and rayon created some jobs for technical specialists, notes Harvard historian Claudia Goldin. But the chief results were more office jobs and a higher demand for basic literacy and numeracy.

Advances in information technology are having a similar effect, Carnevale says. Between 1959 and 1997 the nation added more than five times as many office jobs as technical positions. From a detailed survey of census statistics, Carnevale concluded that at most 13 percent of American workers require higher math (trigonometry or calculus) for their jobs. But roughly 57 percent need significant analytical and verbal reasoning abilities.

At most, 13 percent of American workers require higher math for their jobs.

There are many ways to teach high-level reasoning, Carnevale points out: "We used to teach Latin; math serves that function now. But it's the general ability that's more and more in demand, not the specific one." If that is true, then traditional math and science instruction, with its emphasis on memorizing facts and procedures, does students a disservice.

With a 96 percent employment rate, shortages of hot technical skills are inevitable. But public school reform is a slow and uncertain way to address them. "When the personnel department wants people who have three years of experience with a technology that's only 18 months old," remarks William Aspray, head of the Computing Research Association in Washington, D.C., "they're not going to find them." —*W.W.G. and D.F.*

A Day in the Life of Three Schools

by W. Wayt Gibbs

TASCOSA HIGH SCHOOL, AMARILLO, TEXAS

Most Americans would find much at Tascosa High that is familiar. Students bustle past massive cases full of athletic trophies; they address certain teachers as "Coach." After the bell, hall monitors stop kids without passes. Among the 2,100 students here, "attendance is the biggest problem," principal Bob Daniels says, between loudspeaker announcements about sports teams and social events.

The science and math classes at Tascosa also follow century-old American traditions. In Room 221, Rebecca Evans projects questions reviewing the semester's work in her ninth-grade physical science class. Nearly all the items ask only for definitions or formulas: What is refraction? What is specific heat? What does a diffraction grating do?

Copying from the overhead, several of the students ask nonsensical questions. "What's the unit for welk?" one asks, misreading "work." "Is that $(m + m)/s$?" asks another, misreading the units for momentum.

"The demos are cool," one freshman remarks. He recounts one in which Evans filled a bottle with water and compressed gas, then shot it into the air. "We found that the more water in the bottle, the higher it went." Why? "Because the more water in the bottle, the more compressed the air," he states with confidence, betraying a fundamental misconception about how rockets work. Their 800-page textbook devotes only three sentences to explain that thrust is proportional to the mass of the expelled propellant (the water).

In Michael Miller's chemistry class, senior Clay Estes says that "many science teachers just want you to take notes and learn on your own. But here we often have class discussions; everyone participates." "Coach Miller is a really, really good teacher," agrees Lainie Kitser, also a senior. "But chemistry didn't seem as relevant as biology did. The labs were just following a recipe, and we jumped right into memorizing formulas and the periodic table. If they decided to build a chemical plant in Amarillo, I don't feel like I'd be very informed."

STEVE STARR SABA

MATH CLASS, same as it ever was.

Many reform experts suggest that high school should teach kids science they can apply to real life. But the teachers at Tascosa have few incentives to do that. Jo Meaker created a hands-on marine science course, through which the students become certified to monitor water quality in local reservoirs. Terri Slaughter started a course in anatomy and physiology that made frequent field trips to hospitals and veterinary clinics. But both had their classes cut this year from three to one.

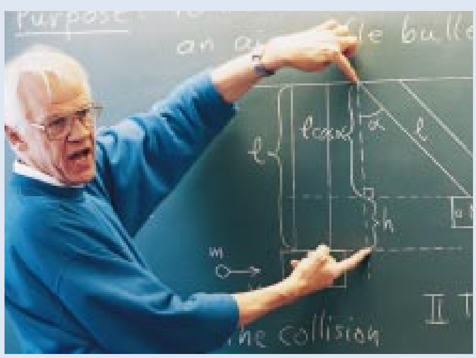
"The dilemma is that the state-required science courses are aimed at college-bound kids," notes Teresa Railsback, a chemistry teacher. "You would like to teach them consumer chemistry so that they can be informed citizens. But you don't want them getting to college and facing two semesters of remedial chemistry." College science courses are rife with memorization and abstract computational problems. And so the tradition continues.

DRAGONSKOLAN, UMEÅ, SWEDEN

Lena Björklund, in white lab coat, glances at a dial on the device into which she pushes a vial of violet liquid. Crowded around her, students compare her actions to the step-by-step instructions on their handouts. In a few minutes, they will mimic the procedure. "The goal of this lab," Björklund explains, "is to learn how to use the spectrophotometer."

Down the hall, Gunnar Källström lectures for 10 minutes on the photoelectric effect. There is no clock on the dingy walls, no bell to signal the start or end of the lesson, no loudspeaker. "Any questions?" he asks, but the only reply is a stifled yawn. He returns to the board, and the seniors diligently copy his notes as he races in 15 minutes through the theories of atomic structure, energy levels, electron excitation. "Any questions?" Silence. "Okay. On to relativity. . . ."

Many in the U.S. might envy Sweden's high schools. On the last international science test, Swedish seniors scored highest in the world. The 2,000 teenagers in Dragonskolan are quieter and more attentive than their Texan peers. Science classes are a paragon of traditional instruction. "We focus on procedures to solve various classes of problems," says Andreas Lindgren, who teaches physics and math. "Ap-



JOHAN GUNSEUS *Pressens Bild*/SABA

AN OLD-FASHIONED LECTURE, with Källström at the board.

plications are barely touched on. The emphasis has been on filling the pipeline with good research people." To that end, sophomores must choose among 16 tracks. Only two lead to college, and those paths commit them to rigorous, theoretical courses in biology, chemistry, physics, and math up to calculus.

Yet the Swedes themselves are unhappy with their schools and have forced the education ministry to make sweeping reforms. Since 1994 it has abolished its national exams and replaced the national curriculum with standards that local schools can achieve however they see fit. It cut back on required courses. And science and math classes are supposed to emphasize applications, historical context and social issues as much as theory and calculation.

After five years, these changes have seeped only into corners of Dragonskolan. In one room, groups of kids in an environmental science class make presentations on how carbon dioxide, phosphorus, freshwater and ozone move through ecological and economic cycles. Anna Malmros, their teacher, asks leading questions that provoke animated discussions on farming practices and government regulations. "The students are encouraged to form opinions on problems and to suggest ways to address them," Malmros explains. "Now we'll work with this information."

Källström's math class is more typical. To American eyes, it is stunningly challenging—these sophomores are already learning basic calculus taught solely in English, a foreign language. But several of the students say that only the English seems interesting and useful.

"May I ask a stupid question?" one girl pipes up at a pause in the lecture. "Is this what is called an integral? Because I don't understand what an integral is." Källström reiterates the terminological distinction between an integral and an antiderivative. The girl's face retracts in frustrated confusion, and she stares again at her book.

BEDFORD ROAD COLLEGIATE INSTITUTE, SASKATOON, CANADA

As in Sweden, high school seniors in Canada earned notably higher science and math marks on the 1995 TIMSS tests than American students did. And since then, Canada, like Sweden, has pushed its schools to overhaul those subjects. But at Bedford Road, a typical school in this city of 108,000 in the Saskatchewan breadbasket, the changes are much more visible than at Dragonskolan or Tascosa High.

"I used to teach in a rigid sequence," says Richard Dybvig, who heads the science department. "But eventually I realized that I was turning out little robots." Dybvig helped to write new curriculum guidelines for the province urging teachers to rely more on open-ended experiments and to talk about the social issues raised by science and technology.

In his advanced biology class, clusters of students puzzle over letters representing a genetic sequence. Dybvig has asked them to find a match in the sequence for a small DNA fragment, and none of the kids have realized yet that they must search for the letters that complement those in the fragment. For 10 minutes he stands aside, answering their questions with his own, until each group figures it out.

He then explains how this same principle is used to do DNA fingerprinting in court cases. Without prompting, the kids pepper him with questions. "If you have the sequence for a certain disease, does that mean you are guaranteed to get it?" (Dybvig talks about genetic propensities, using breast cancer as an example.) "If you could alter genes for aging, could you live longer?" (He admits that he does not know, but he summarizes recent research on the limits of cell division.)

"For 90 percent of the course, I let them choose their own curriculum," Dybvig says. "'The topic is energy,' I'll say. 'Tell me what you want to learn.' As we move toward where they want to go, they invariably realize that they have to know certain basic facts and principles. But they want to know them."

The students have come to expect what they learn to make sense and be relevant. In a precalculus class for juniors, Kevin Sawatzky graphs an equation on the board, describing each step of the process. At every turn, several students call out "How do you know that?" He stops, explains and moves on only when they are satisfied.

"What's this useful for?" one fellow asks. "I'll give you some electrical engineering problems that use rational functions," the teacher promises. "How's that?" "Cool," the boy says.

ROBBIE McCLARAN SABA

DEDUCING A THEORY,
Bonny (*in yellow*) gets advice from Stonehouse.

"When we do labs, we usually head into them blind. Later we work up our own theory and compare it to what's in the book," says junior Jordan Bean. "It's more fun that way," adds Jesse Campbell. "And it keeps you from cooking your results."

Upstairs, Norman Stonehouse is jumping about a chaotic room full of seniors as they collide wheeled carts on tabletops. Ticker tapes and one ancient PC measure the carts' speed before and after the collision. "I told them to find out whether momentum and kinetic energy will be conserved," Stonehouse explains. "But it's up to them to decide how, and they won't know the answer until they compile their data."

"What I like is that we get the skills to get knowledge rather than having the knowledge force-fed to us," remarks Ellie Bonny, a senior. "Their next challenge is to determine the velocity of a marble coming out of a slingshot," Stonehouse says. As he straightens the room at the end of class, and the students trickle out the door, the boys and girls talk animatedly, but not about gossip, or sports, or music. They talk about physics.

Continued from page 88

concurs. "It is preparation for further schooling, not for real life."

The evidence suggests that in practice the supply of scientists and engineers is controlled by universities, not by secondary schools [*see box on page 89*]. Of the 305,000 students who took introductory college physics courses in 1988, only 1.6 percent went on to get a bachelor's degree in the subject. The crop yielded a scant 700 doctorates. If the U.S. needs more scientists, says Glen S. Aikenhead of the University of Saskatchewan, the quickest and most reliable solution is to weed out fewer aspiring undergraduates.

There is good reason, too, to doubt that public school science has much influence on economic competitiveness or productivity [*see box on page 89*]. And if science education is in fact a weak and clumsy lever for boosting research or for moving the economy, then much of the science and math that schools try to teach is pointless.

"When I and other researchers looked at the science that people need to know for decisions that adults actually make—whether they were judges in court cases, politicians on planning committees, poor people budgeting for energy costs or parents who have children with special medical conditions—we found that idealized, abstract science is completely useless," Aikenhead says.

The false crisis in science education masks the sad truth that the vast majority of students are taught science that is utterly irrelevant to their lives—and that "scientists are a major part of the problem; many think that the system is a good system because it produced them," argues William F. McComas of the University of Southern California.

"There is plenty of time after high school for scientists-to-be to learn the minute facts of science," he says. What they need from the schools, Hurd elaborates, are the higher thinking skills "to distinguish evidence from propaganda, probability from certainty, rational beliefs from superstitions, data from assertions, science from folklore, theory from dogma." And opportunity from crisis.

W. WAYT GIBBS and DOUGLAS FOX both live in San Francisco. Gibbs is senior writer for Scientific American. *Fox is a freelance science writer.*

For an enhanced version of this article, go to the Scientific American Web site at www.sciam.com

Six Steps toward Science and Math Literacy

SCIENTIFIC AMERICAN asked experts in science education for feasible, proven ways to improve science and math instruction in the public schools. Here are some of their responses.

1 Replace memorization with exploration and invention.

Arthur L. White, executive secretary, National Association for Research in Science Teaching

Traditional science instruction follows three steps. First, teachers use textbook readings and lectures to introduce new terms and concepts. Next, they solve sample problems at the board and assign practice work. Finally, they hand out step-by-step instructions for a controlled laboratory experiment, the outcome of which the students are already supposed to know.

Well over 30 years of cognitive science research and trials in classrooms have revealed serious flaws in this technique. At root, the problem is that children, when faced with new information, make different connections than adults do. "Density equals mass divided by volume," a child is told—and immediately tries to relate this to firsthand experiences: attending Sunday "mass," turning the "volume" knob on the radio, being called "dense" by a sibling. Too often the child gives up in frustration.

We now know of a better approach, called a learning cycle. It also uses three steps. But the experiment comes first, and students are encouraged to explore phenomena however they wish. The teacher then helps the students to find patterns in the data and to form hypotheses—just as a scientist would—about the underlying rules. Only then does the teacher put labels and terms to what the kids have observed and invented. The final critical step is to apply the knowledge through field trips, more experiments, realistic problems, readings and other means of connecting the new knowledge to what students see as "real life."

Numerous studies have found that students taught using this approach retain more of what they learn, look at science with greater enthusiasm, perform high-level reasoning tasks better and solve real science problems more adeptly.

2 Focus the high school curriculum.

William H. Schmidt, U.S. national coordinator, Third International Math and Science Study (TIMSS)

The results of TIMSS confirmed a long-standing criticism of American schools: that the curriculum they teach is a mile wide and an inch deep. With few exceptions, U.S. schools try to cover far more topics than those in other countries do. American

B. DAEMMRICH *The Image Works*

REAL-WORLD RESEARCH
that allows kids to test their own theories is best for teaching science, many experts say.

teachers are also more likely to repeat the same information from one grade to the next and to cover little or nothing in depth.

Concentrating instruction on fewer key concepts could substantially improve science literacy. It would also make room for long-term projects that build kids' understanding of how science functions outside the lab.

In one high school on the San Francisco peninsula, for example, biology students surveyed the plant and animal species inhabiting marshlands that faced rezoning. The students had to frame their questions in consultation with local officials, plot a research strategy, conduct the investigations, collect and analyze the data, and present their findings to the city council. In the process, they learned about a range of organisms, about the life that could be sustained in different ecological niches and many other things—all at a more profound level than can be gleaned from a textbook or from lectures.

The *National Science Education Standards* and the AAAS *Benchmarks for Science Literacy* lay out a core set of ideas and facts that every child can and should learn, according to the preponderance of research and years of debate among scientists, teachers and the public. A few states and school districts have drawn heavily on these documents in crafting their own curriculum standards. The rest should follow suit.

3 **Select math textbooks for the right reasons.** *Gerald Kulm, Project 2061 program director, American Association for the Advancement of Science (AAAS)*

Deciding which textbook to use is one of the most important professional judgments that math teachers make. But it can be among the most difficult as well. Most math texts for sale in the U.S. are so broad, so repetitive and so focused on terms and computational procedures that they virtually guarantee that many children will fail to grasp the mathematical concepts that would be of most use to them in adult life. Too often math books are selected because they are pretty and meet superficial checklists. Deeper comparisons require money, time and special expertise.

But now there is a *Consumer Reports* of math textbooks, and schools should avail themselves of it. Project 2061 has rigorously analyzed the content and instructional quality of more than a dozen middle school math texts. Only four were rated highly. The full report is available at http://project2061.aaas.org/matheval/ on the World Wide Web. This autumn Project 2061 will also release the results of its analysis of science texts.

4 **Eliminate low academic tracks.** *Robert M. Hauser, professor of sociology, University of Wisconsin–Madison*

Much more than in other nations, U.S. schools tend to separate children into advanced, regular and slow classes, especially in math and science. Sometimes based on standardized tests—often inappropriate ones—most elementary schools teach different material to different groups of students for at least part of the day. The practice is more explicit in secondary schools. One result is that fewer than one quarter of American high school students receive any substantial exposure to physics.

In a report published this year by the National Research Council, I and others cited convincing evidence that low-track classes put much less emphasis on the higher-order knowledge and thinking skills that are strongly associated with future success. In theory, remedial classes help low-tracked students catch up. But studies have found that lower-track classes typically have a poor curriculum, low expectations and ineffective teachers, so the disparity between students on fast and slow tracks grows over time.

5 **Assess performance, not regurgitation.** *J. Myron Atkin, chair, National Academy of Sciences Committee on Science Education, K–12*

Science courses in the public schools tend to emphasize recall of isolated information, with little attention to deep comprehension of science principles or the ways in which science works. The surge in statewide tests as a way of holding schools accountable has exacerbated this problem, as has TIMSS. It is well established that if tests have consequences, then teachers teach to the tests.

Schools ought instead to evaluate students by how they perform tasks that match curriculum goals. They could also assign grades based on reports, presentations and experiments that reflect the aims of the course.

Evidence suggests that examinations by themselves do nothing to help students understand science better; some are even counterproductive. Other kinds of tests, however, could actually improve learning. Schools in Pasadena, Seattle, Anchorage and elsewhere have found that when teachers give students frequent feedback—not as quizzes but as conversations—the kids grow better at judging their own achievement and that of others. If the students are clear on what they are trying to learn and what they have yet to grasp, they improve faster and learn more.

6 **Build on kids' preconceptions about science.** *Senta A. Raizen, director, WestEd's National Center for Improving Science Education*

Students don't come to the science classroom empty-headed but arrive with lots of strongly formed ideas about how the natural world works. Many believe, for example, that some materials (such as wool) are intrinsically warm, whereas others (such as metal) are cold by nature. These misconceptions are held tenaciously, even in the face of formal science instruction to the contrary. In one study, when asked what causes the seasons, a large number of Harvard University seniors replied that in summer the earth is nearer to the sun than it is in winter.

Science textbooks frequently claim to take account of students' preconceptions, but in fact they do so only peripherally, if at all. There are now powerful strategies for dealing with misconceptions. The first step is to get children to state their beliefs. Teachers can then use some of the students' ideas as starting points for experiments and can discuss why scientifically accepted explanations might be better.

When sixth graders were given this kind of instruction, they performed better on conceptual physics problems than did 11th and 12th graders who had been taught conventionally in the same school system. Other trials have met with similar success. Teachers clearly must have a deep understanding of their subject to make this work. But there is now a computer program, called Diagnoser, that can expose students' beliefs about physical phenomena and suggest activities to help them develop a more accurate intuition. The Diagnoser software is available on-line at http://weber.u.washington.edu/~huntlab/diagnoser/

SPECIAL REPORT:

HIGH-SPEED DATA Races Home

The global network is entering a new phase in its evolution, one that will spawn new applications and make dial-up modems a thing of the past

by David D. Clark

Within a decade, most people in developed countries will have access to Internet connections that are tens if not hundreds of times faster than the ones in common use today. Although that development may not sound exactly earth-shaking, it will in fact herald an entirely new stage in the evolution of that global network.

Those high-speed connections to the home—whether they take the physical form of a telephone wire, a cable television line or a satellite link—will give rise to an entirely new set of applications. Not only will enthusiasts be able to jump instantaneously from page to page on the World Wide Web—and will therefore use the Web much more often—they will also be able to enjoy applications that exist today only as crude prototypes or as concepts in the minds of visionaries and entrepreneurs. Real-time high-fidelity music, telephone, videoconferencing, television and radio programs could all be provided by a single service company over a single hookup. There will be new entertainment options, such as movies-on-demand, and new features, such as the ability to call up information about a movie's director or its actors as they appear on screen. Users will be able to play on-line games—live—against many contestants scattered around the

SLIM FILMS

RACING TO THE HOME: at least five different technologies are competing to deliver information at vastly higher rates than are possible with today's ubiquitous dial-up modems.

globe. People separated by thousands of kilometers will be able to share virtual-reality experiences and work effectively together on a business or academic project.

The rapid rise of very popular Internet applications like the Web is driving industry to build the infrastructure needed to bring high bandwidth, or "broadband," communications to the home. It is estimated that in the U.S., one home in four now has some kind of access to the Internet. Most people now connect using a dial-up modem, a device that converts back and forth between streams of data and patterns of audible-frequency tones, enabling the data to be sent down telephone lines originally designed to carry voices. At the other end of the line, an Internet service provider acts as a kind of portal through which the subscriber can contact and exchange data with countless nodes around the globe.

Dial-up modems are easy to use, and most computers come with one built in. But their performance is limited. In addition, the need to place—and pay for—a telephone call to establish a connection to the service provider means that access to the Internet is not continuously and conveniently available. Once the broadband technologies described in this special report emerge, people will receive and send text, images, audio and video over the Internet at vastly greater speeds, with virtually no delays. Indeed, the Internet will always be "on" at various screens in the home, ready to help at the single click of a key or voice command. The technologies will bring a host of new data, multimedia and television services. And they will do all this at an affordable price.

Enthusiasts will jump instantaneously from page to page.

Wiring the Home

The difference in speed among ways to connect to telecommunications services such as the Internet is striking. The fastest modems in general use today receive and transmit data at 56,000 bits per second (56 kilobits per second, or kbps). This is the limit at which most home computers can connect. The personal computer in an office is typically connected to others in the company with a local-area network; the most common, Ethernet, has a raw speed of 10 million bits per second (10 megabits per second, or Mbps)—about 200 times faster than the modem. But unless the company has a dedicated high-speed line to an Internet service provider (ISP), the worker's Internet experience is limited by the modem, too.

Some companies have high-speed connections, but very few homes or small businesses do. Furthermore, people do not usually leave their computer and modem on all day, connected to their ISP all the time; the charges for this continual use of a phone connection would be prohibitive. This noncontinuous connection has two implications. First, when people want to use the Internet, they must wait while the modem connects, which hinders casual or frequent use. Second, there is no way to exploit applications such as receiving a phone call over the Internet, because the recipient cannot be contacted if he or she is not already connected.

Ultimately, the desire for broadband communications to the home derives from the increasing speed of computers. Computers are on a development path that improves performance by a factor of 10 every five years. This steady advancement regularly prompts a wide range of unanticipated applications; the World Wide Web was basically just a bright idea only nine years ago. Yet the increasing speed of computers will not result in faster communications applications if users remain stuck behind a dial-up modem; 56 kbps is about as fast as this hardware will ever go.

The assortment of wires and cables that run to most homes also represents a barrier to high-speed operation. None of these links was intended for data transmission at any speeds, let alone extremely fast ones. Twisted pairs of copper wires were put in to support phone service; coaxial cable carries television signals; and power lines, of course, convey electricity.

Nevertheless, engineers are trying a variety of approaches to connecting homes for high-speed data communications; this report describes five of them. The first two use clever technologies to wring the most out of existing wires to the home: hybrid fiber-coax makes use of the cable TV industry's infrastructure, which includes fiber-optic lines in addition to coaxial cable; digital subscriber line, meanwhile, exploits frequencies much higher than those used to convey conversations to send high-speed data over pairs of copper telephone wires. The third approach is to run an entirely new wire to the home—a fiber-optic cable. There are several configurations for such a system, including fiber-to-the-curb and fiber-to-the-home, depending on how far the fiber reaches toward the residence.

Wires and fibers can be abandoned altogether. The fourth and fifth technologies are both "wireless"; in addition, they each have an analogue in the wireless telephony arena. Various planned broadband Internet-oriented satellite networks would work in a manner similar to the Iridium satellite-telephone system in that the orbiters would communicate directly with the subscriber. In the case of the Internet system, the user would access the data via a small dish antenna. The other approach, known as local multipoint distribution services (in Canada as local multipoint communications system), is similar to a cellular telephony network; it uses radio waves to transmit data between towers and receiver dishes mounted on homes.

There is no single, simple metric to compare these broadband technologies. It would be nice to rank them on comparative speed, for example, but almost all of them are capable of operating over a range of speeds, depending on how they are actually implemented.

By considering the key features of each, we can at least make reasonable inferences about likely answers to some of the fundamental questions, such as: Will one technology win out over the others? Will several compete? Will broadband service be more affordable anytime soon? Extremely powerful industry forces now at work will settle these issues.

Next on Channel 92: Lightning-Fast Internet

Although the cable TV industry developed its widespread coaxial cable network just to offer television, it aggressively upgraded its equipment starting in the late 1980s to support other services, including Internet access and even telephone service. The enhancements involved laying fiber-optic lines from key signal distribution points most of the way to residential areas, then using the original coaxial cable to distribute the signal among the homes in a neighborhood or part of a town. By using fiber-optics only where it was most needed, the cable companies spent far less than would have been necessary to replace the entire network with the optical lines. Nevertheless, even this partial use of optical fiber improved the television signal while making it possible for the network to carry two-way Internet and telephone traffic. To access the Internet, the homeowner must have a cable modem, a device that attaches to the cable just like a TV converter box but decodes and manipulates data rather than television signals.

The capacity of a hybrid fiber-coax (HFC) system is considerable. Just one of the many television channels offered to subscribers can carry almost 30 Mbps to the home. Moreover, technicians could allocate multiple channels for broadband Internet if the demand generated enough revenue to justify displacing other television channels.

One cable television channel can carry 30 Mbps.

In an HFC system the data channel is shared among the homes linked by coax to the end of the local fiber-optic line. Thus, the actual data rate achieved in any individual home depends on the number of users sharing the channel at a given time. But a well-designed system can give each user bursts of data from the Internet at speeds around 10 Mbps. There is also a lower-speed channel in the reverse direction to carry data from the home back to the Internet.

From the Telephone Switch to You

The telephone industry has developed a number of novel techniques to transmit data at high rates over the copper-wire pair designed to convey phone calls. For example, a service called integrated services digital network (ISDN) has been around for years; it operates at 64 or 128 kbps. But a pricing quagmire and an introduction long confounded by regulatory issues left it only marginally more useful than fast modems today. A much faster service known as T1 was initially developed for bringing multiple voice connections to a business; it can carry data at 1.544 Mbps, and some small businesses and even home offices have begun using it for data access. Still, T1 has traditionally been priced for commercial voice access, which is much more costly and more than most people can afford for data access.

The current promising telephone technology is digital subscriber line (DSL), which operates over conventional phone lines but achieves higher data rates using different electronics at the ends of the wire. The twisted pair from a home typically runs to a building not far away called a central office, where it connects to a switch. A switch is a complex piece of equipment that routes telephone calls to other switches or phones as necessary. Most of them were designed only to carry voice and have no special options to handle high-speed data. Dial-up modems work only because their designers went to great trouble to create coding schemes for data that the existing switches can carry.

DSL is much faster because it does not use the existing switching equipment. New switches are installed in the central office to exploit the full data-carrying capacity of the wires, which normal phone calls simply cannot use. DSL also uses more sophisticated schemes that code the data in a bandwidth that is larger and occupies much higher frequencies than the one used for voice.

There are several variations of DSL, depending on the distance from home to central office. At present a home must be within about five kilometers of the central office to make use of this scheme. The most widely developed version is asymmetric DSL, or ADSL. It is capable of delivering 3 to 4 Mbps to the home and a slower rate back from the home, typically a small fraction of a megabit per second.

Fiber-optic lines have a number of advantages over copper pairs or coaxial cables. Most important, fiber can carry data at a much higher rate: millions of megabits per second. If optimized, a single fiber could carry all the phone calls being made at any instant in the U.S. Today there are hundreds, if not thousands, of fibers nationwide that serve as the backbone of existing telephone, cable TV and Internet networks.

Signals are sent by shining a beam of laser light down a fiber. Because of the optical qualities of the fiber, the light can follow the twists and turns of the strand, coming out the other end where it can be detected. The laser is turned on and off at a rate of billions of times a second, generating a pattern of light pulses that correspond to bits and are sent down the fiber and converted at the receiving end back into an electrical signal.

As with any kind of infrastructure, it is very expensive to install a network linking many homes. One way to reduce the cost is to use one fiber to serve a cluster of residences, rather than having a separate fiber for each home. This cheaper system, which seems to provide a fairly good cost/performance trade-off, is called fiber-to-the-curb. One fiber comes from a central office to a small box near the curb, and from there the traditional copper pairs or coaxial cables connect to perhaps 10 or 15 homes.

Will LEO Roar?

Of all the broadband options now emerging, satellite-based service is the most advanced and the most risky—from both a technical and an investment perspective.

Most existing communications satellites are geosynchronous. This means they are at exactly the right height above the earth so that they orbit at exactly the same rate as the earth turns. The result is that they are fixed in the sky with respect to a receiver on the earth. Thus, home satellite dishes for receiving TV signals don't have to move to track the satellite.

Yet geosynchronous satellites have several drawbacks. They are a long way up (about 36,000 kilometers), so there is about a quarter-second delay in sending a signal up and back. This delay degrades many forms of data transmission. The distance also means that the satellite must have a powerful transmitter or transmit at a low data rate. Finally, there is only so much room in geosynchronous orbit, and it is already mostly full.

The next generation of satellites being readied for deployment will have much lower orbits. Instead of seeming stationary, they will pass by overhead. If enough of them are placed in orbit, at least one will be in range at any time over any given point. These low-earth-orbit (LEO) satellites will also be engineered to communicate with one another [see "New Satellites for Personal Communication," SCIENTIFIC AMERICAN, April 1998]. This way, a remote unit at one residence can talk to another unit somewhere else by sending data up to whichever satellite happens to be overhead at the moment and having that satellite forward the message around in space to the satellite that happens to be over the second remote unit.

LEO systems have many potential advantages. Because the orbital altitude is typically below 2,000 kilometers, the propagation delays are very short. Because the satellites can operate at various altitudes, more orbits are possible, and many systems could be deployed. The low orbit also means lower radio transmission power, so the home needs only a small, unobtrusive antenna.

The cost of putting a LEO satellite system in place is very high, because dozens of satellites have to be launched. And it has yet to be demonstrated that demand justifies this cost. Nevertheless, LEO voice systems such as Motorola's Iridium configuration are already in place, and several companies are planning LEO data systems with projected aggregate data rates up to one gigabit per second.

Wireless on Terra Firma

Broadband service can also be ground-based and wireless, and indeed those are the distinguishing characteristics of a diverse set of technologies being explored for the consumer marketplace. This report focuses on a particular option, called local multipoint distribution services (LMDS), which is receiving a lot of attention from access providers. LMDS systems use a radio signal of very high frequency (28 gigahertz).

The basic premise behind wireless networks is that the major cost of installing any broadband system based on wire or fiber is not the cable itself but the labor to install it. Thus, they eschew wire lines. Instead, like cellular telephones, these networks use radio connections from a base station antenna to remote units at residences.

Engineers are developing a number of configurations, which can be categorized by the distance between base stations, the data transmission rate and issues such as whether the remote units can be mobile. Unlike cellular telephones, Internet users are generally stationary, which greatly simplifies the system.

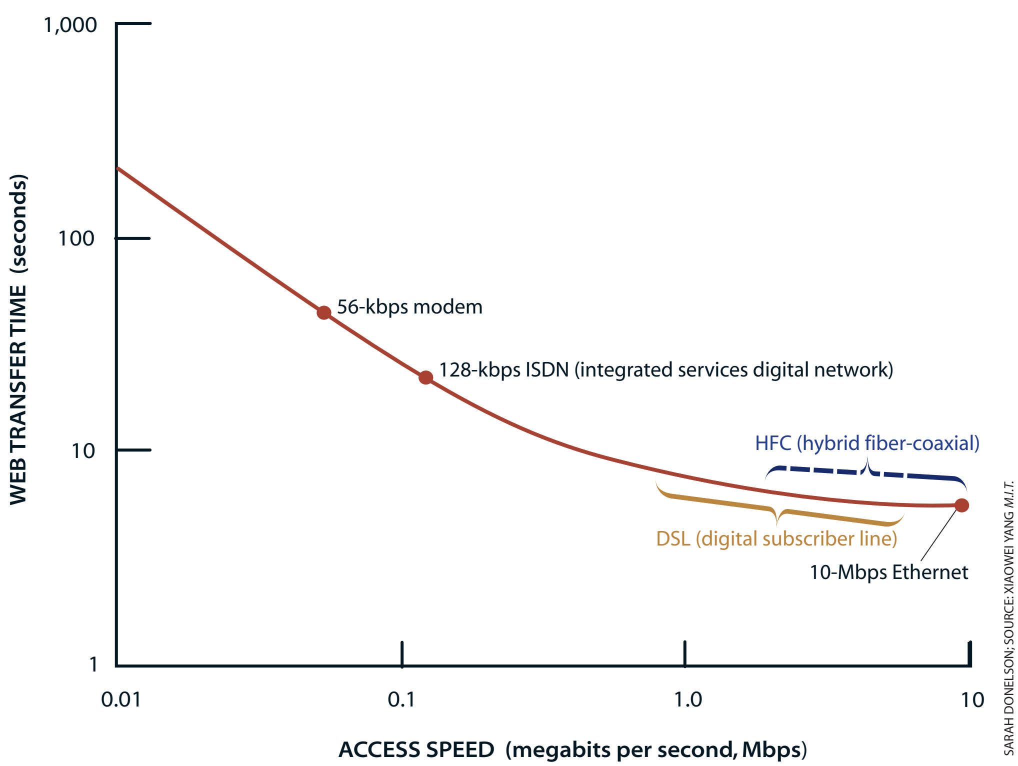
In fact, one such wireless system for data is designed to use the existing cellular telephone towers and thus must operate using the spacing of those facilities. So far these systems offer only modest data rates (10 to 50 kbps) and are marketed to users on the move, not for residential access. Still, the cellular industry has plans for more aggressive use of its towers, to deploy services with data rates up to 1 Mbps to the home. Commercial service is expected in a few years.

Other wireless systems are based on much closer spacing of base stations. Smaller antennas would be put on top of telephone poles or even hung from lines between poles. These systems would be more costly to install, because they would require more base stations but could offer higher data rates given that the wireless distances would be shorter.

The very high frequency of LMDS imposes some limitations, because the radio waves travel only in straight lines and are therefore blocked by buildings and other obstacles. Even more problematically, they cannot penetrate moisture and thus cannot go through foliage very well. But the very large allocation of bandwidth (1.3 GHz) allows for the potential creation of very high speed services to the home. Early trials of LMDS systems are happening now, involving perhaps 10,000 subscribers in the U.S.

How Fast Is Fast Enough?

It is clear from these brief descriptions that the various broadband systems differ in the performance and range of services they can provide. For example, ADSL does not have the capacity to carry television, so it is suitable only for data



HIGHER-SPEED ACCESS makes the Internet feel more responsive by reducing the time for data transfers. The curve shows how access speed affects the total time needed to download a complex Web page, with included images and subcomponents, from a site across the country. Obtained by a detailed simulation of network operation, the curve shows that for this example a 56-kbps modem might take more than 40 seconds, whereas the broadband technologies need just under 10 seconds. Not all the broadband options are shown: for most PCs, the 10-Mbps Ethernet link sets the speed limit, and even fiber-to-the-home (off the scale at 100 Mbps) cannot beat about six seconds set by network processing times and the speed of light.

and voice. Some forms of fiber-to-the-curb support TV service, some only voice. The various satellite systems currently being deployed are specialized for voice, data or television.

These systems have been in the works for a while, so the fast rise of the Internet has imposed a new set of design challenges. A telephone call requires a known quantity of network capacity, and a system to carry telephone calls can be designed for an expected number of calls. Similarly, a cable television system is designed to carry a known number of television channels. But the speed of Internet service can vary greatly. So right now system designers and broadband entrepreneurs are left to figure out how much money people will pay to go faster—which basically boils down to determining how much happier higher speeds make them.

Designers are also plagued by uncertainties in future user demands. The most popular application of the Internet today is the Web, which has one set of capacity requirements. But the Internet can carry all kinds of applications, each with different communications requirements, and it is not clear which will become popular over the life of a system installed today.

Given the wide range of systems and technical requirements, it is tempting to speculate which broadband technology will be the winner. But technical differences will have minimal influence on deployment. The various systems are all technically feasible. All of them, except LEO satellites for data only, have been demonstrated and are even being installed to varying degrees. The real barrier to widespread broadband access is the cost of installation. As might be expected, economics and business structure are driving deployment decisions.

Industry estimates suggest that the cost to newly wire a neighborhood for broadband, so that the cost of installation is shared across all the residences, is roughly $1,000 a home. Because there are about 100 million homes in the U.S., the implication is that perhaps $100 billion must be spent to provide a new wireline connection to every home in the country. This is a huge sum to justify, especially because the importance of the Internet (and broadband access to it) is still proving itself. To wire one home at a time is much more costly, so any piecemeal wiring of isolated consumers would be even less feasible.

Telephone and cable companies are therefore moving forward with incremental improvements that are substantially cheaper than a total replacement. Today, not surprisingly, cable television companies are selling broadband Internet service based on their hybrid fiber-coax networks and cable modems. Meanwhile telephone companies are offering broadband Internet service based on ADSL and their ubiquitous copper pairs. The eventual mix of cable and DSL technology in the U.S. will thus have nothing to do with their relative technical merits but everything to do with the relative levels of investment and marketing by these two market forces.

There are few investors who will back the installation of a whole new wireline facility such as fiber-to-the-home. But when a new installation is called for, say, to serve a new subdivision, there is considerable motivation to install as modern a system as possible. Thus, fiber-to-the-curb may be seen in new installations, most likely brought by either the local phone or cable company. Intriguingly, fiber-to-the-curb or fiber-to-the-home may also enable electric utilities to enter the data business, at a time when many are seeing successful challenges to their former monopolies on power generation. One tremendously valuable resource many electric utilities still have are rights-of-way—which are, basically, the poles and lines that run up and down neighborhood streets and major thoroughfares. It would be a fairly straightforward matter to string new data communications lines alongside the old power cables. The possibility underscores the idea that each of the wireline technologies should be seen as occupying a business niche, rather than competing with one another on technical merits.

A single fiber could carry all the phone calls in the U.S.

Companies that want to get into the broadband business but that do not already own a wire to the home or right-of-way are left with wireless or satellite. Erecting these systems, particularly in municipal regions with high population densities, is less expensive than putting in new wires but still very costly. Consider AT&T, which as a long-distance company is not wired directly to residences. AT&T has committed more than $100 billion in acquiring cable companies such as giant Tele-Communications, Inc., to give it broadband paths to some portion of American homes (ironically, via TCI's extensive cable television networks). To serve other parts of the country where these mergers do not give it wireline access, AT&T is developing wireless options.

Clash of the Titans: Cable versus Telcos

Broadband technologies have not appeared in the marketplace as rapidly as some observers had hoped, and frustration with slow deployment has led to speculation that perhaps there is not enough real demand to justify the large investments required. The Internet's quick rise will speed things up. Deregulation of telecommunications was supposed to have encouraged phone companies to offer television and cable companies to offer phone service, thereby improving competition in each sector. Little has actually happened. But huge demand for the Internet, which can be carried just as readily by both industries, is prompting them to collide for the first time.

Whichever industry invests the most in infrastructure might very well grab the lion's share of the broadband market. At the moment, the cable companies, with their hybrid fiber-coax technology, have the largest share. But the telephone companies have the capital—and now, with DSL, the technology—to make an impression in the market and are finally starting to do so. It is too soon to say whether wireless and satellites will mount a significant challenge to cable and DSL, and fiber-to-the-home seems destined to remain a prohibitively expensive proposition for at least the near term.

In the longer run, the consumer will be best served if all of them succeed, fostering more vigorous competition and more extensive choice. It is one of the Internet's greatest strengths, in fact, that it can operate over all these technologies. Happily, there does not need to be one winner to take us to the next stage in the Internet's evolution, regardless of the specific shape that stage finally takes. SA

The Internet via CABLE

by Milo Medin and Jay Rolls

Using cable Internet services for the first time can be a breathtaking experience. Images and text flash before your eyes instantly. Full-motion video and audio play without jitter. When you see this, you realize that this was how the Internet was meant to be. Even for Internet oldtimers, it's like a whole new world.

The cable television network has emerged as the early leader in providing such high-speed data access in the home. With more than a million cable modem subscribers now in North America, the system has matured from a string of experimental deployments in 1995 to a mainstream service available in most major cities.

Internet access over cable runs at speeds up to 100 times those of the traditional dial-up world. This raw speed is the catalyst producing the dramatic change to typical Internet services. And the connection is "always on," enabling users to call up a site immediately as the spirit moves them. Gone are the days of having to log in to the network. Telephone companies have recently started to introduce their own high-speed services, but so far their offerings are considerably slower than cable and in almost all cases more expensive. One cable operator, Cox Communications, offers monthly service for only $29.95 if the customer provides the modem.

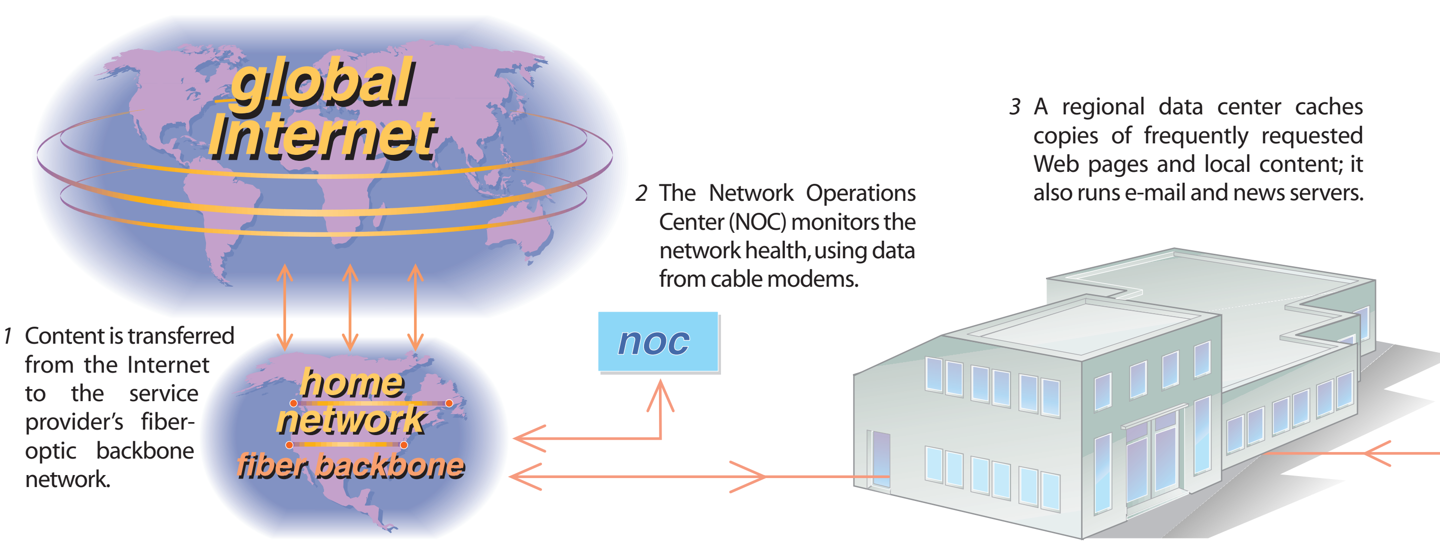
How does cable achieve these data rates? In the late 1980s and early 1990s cable operators started deploying fiber optics in their networks. And as everyone knows, a diet rich in fiber is good for you. Cable companies ran fiber out to individual neighborhoods and made use of the existing network of coaxial cable—the familiar line that screws into your TV or set-top box—to reach the "last mile" to each home. The optical fibers connect the cable operator's central facility (the "head end") to each neighborhood area (the "node"), which typically encompasses about 1,000 homes, each a potential customer.

Fiber has greatly increased the capacity and reliability of cable TV networks. With a cable Internet connection, data occupy the space of one TV channel. Tune to this channel with your TV, and you'll see only static, but connected to your cable modem it becomes a data stream flowing at about 40 megabits per second (Mbps), which can then be relayed to your personal computer at rates up to 10 Mbps. The fiber network also allows signals to be sent back from the home to the head end, making telephone and interactive video services possible. About half of all North American cable homes already have this two-way capability, fewer in Europe and Asia.

More than a Modem

A cable modem can connect to more than one PC in the home, with excellent support for in-home networks. These home networks, coupled with the always-on nature of the service, will promote the proliferation of "smart" residential devices—such as microwave ovens that read a product bar code and call up the appropriate cooking plan from an Internet database or a touch-sensitive screen in the kitchen (perhaps built into the door of your refrigerator)—that puts a wealth of information at your fingertips.

The Architecture of a Hybrid Fiber-Coaxial Network



Only cable networks are well equipped to provide hybrid TV-Internet services, as well as superfast on-line access

Cable modems use a number of advanced techniques to perform their duties. In fact, "cable modem" is a bit of a misnomer, because it has several additional roles: directing traffic; encrypting for security; validating signals; and tuning the proper channel.

Because the coaxial cable is shared within a neighborhood, the modems must equitably dole out bandwidth to customers, ensuring that no single customer can monopolize the total available bandwidth. As the number of users grows, the cable operator shrinks each service area to maintain adequate bandwidth. All data transmitted over the cable network are encrypted for privacy, and each modem has its own unique cryptographic key.

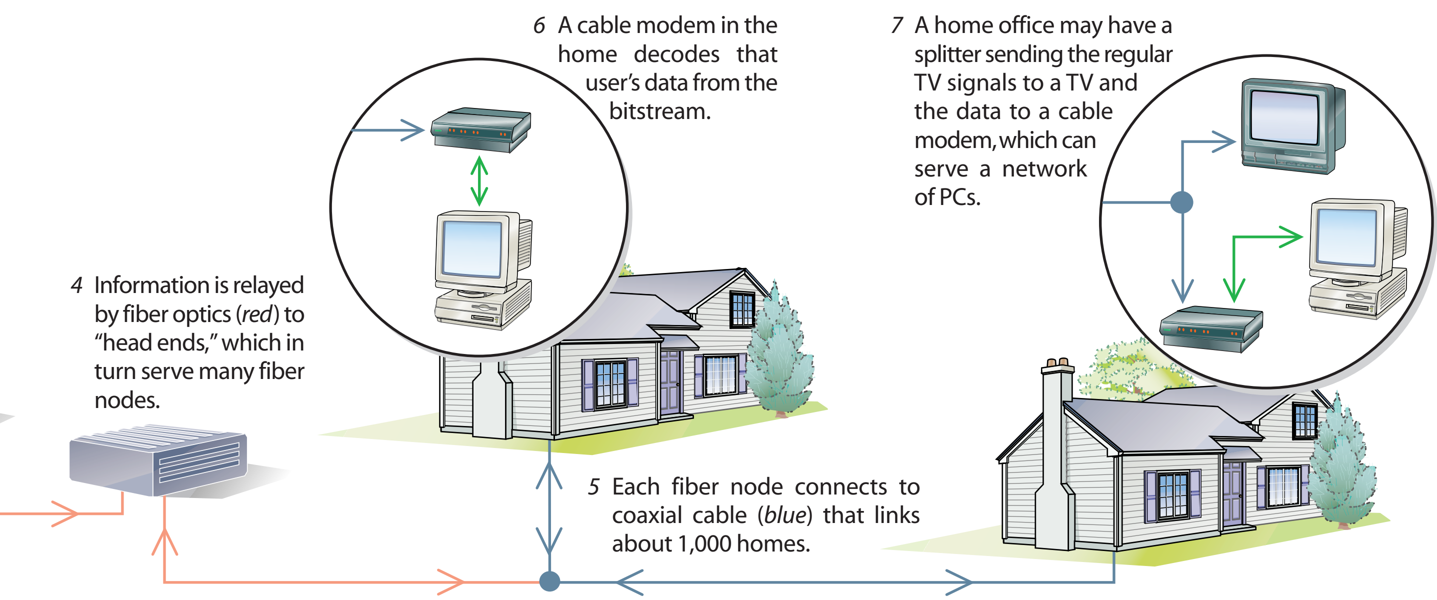
The modems supply extensive information on the network status to the broadband service providers, such as Excite@Home. Automated software updates for the modems can be centrally coordinated, and service anomalies can be flagged without human intervention. Early-warning signals from the modems let the provider respond to problems before they affect service.

An important element for conveying a high-quality broadband experience is a caching system. For example, Excite@Home stores copies of commonly requested Internet content on local servers close to subscribers. The local copies can be fetched without having to go all the way to the end destination, speeding up access to Web pages.

Cable modems will enable a wide variety of services. High-speed access to the Internet is the most obvious use for cable modems, but second-generation applications are quickly emerging and will dramatically affect many traditional services in the home. Makers of the set-top boxes that connect to the television in most cable systems are using the same technology for transporting data to and from the TV. Surfing the Web or reading e-mail on your television will be as common as on your PC.

But what really thrills television executives and advertisers alike is the integration of TV with the Internet, allowing subscribers to move back and forth seamlessly, from one medium to the other. For instance, while you're watching *Dilbert* you could have a window open on your TV for chatting with other viewers about what's happening on-screen. Or while watching a movie, you could call up information about the director and the actors. Perhaps most alluringly from a corporate standpoint, advertisers will be able to offer one-click purchasing of merchandise that appears on the screen. Because virtually every American household has a TV, whereas PCs are not yet so ubiquitous, such a TV-based system greatly expands the potential audience for these services. Only the cable network is well equipped to offer such hybrid services.

As cable operators overcome the technological challenges, they are turning their attention toward execution: deployment, service and marketing. Cable executives are scrambling to morph their companies into full-fledged telecommunications companies. And someday soon images, sounds and data from all over the globe may come at you at remarkable rates, and you will realize that what you are experiencing is not your father's cable TV network. SA



IAN WORPOLE

DSL: Broadband by Phone

by George T. Hawley

Does the humble telephone line, the Victorian technology that transformed the world, have a major role to play in shaping the third millennium? Can a mere pair of thin copper wires twisted around each other transmit Internet data reliably and securely at blazing speed, making it possible to view high-fidelity moving images, sound and vast amounts of data on your personal computer screen or television? The answer is yes, as the growing success of digital subscriber line (DSL) technology abundantly demonstrates.

These trusty copper wires, installed in more than 600 million phone lines worldwide, provide high-quality, dependable voice service, but for a century most of their transmission capacity has lain dormant. DSL technologies exploit this resource, bringing a 50-fold increase in speed to millions of modem users, accelerating the growth of electronic commerce and changing the nature of communications.

Raising the Speed Limit

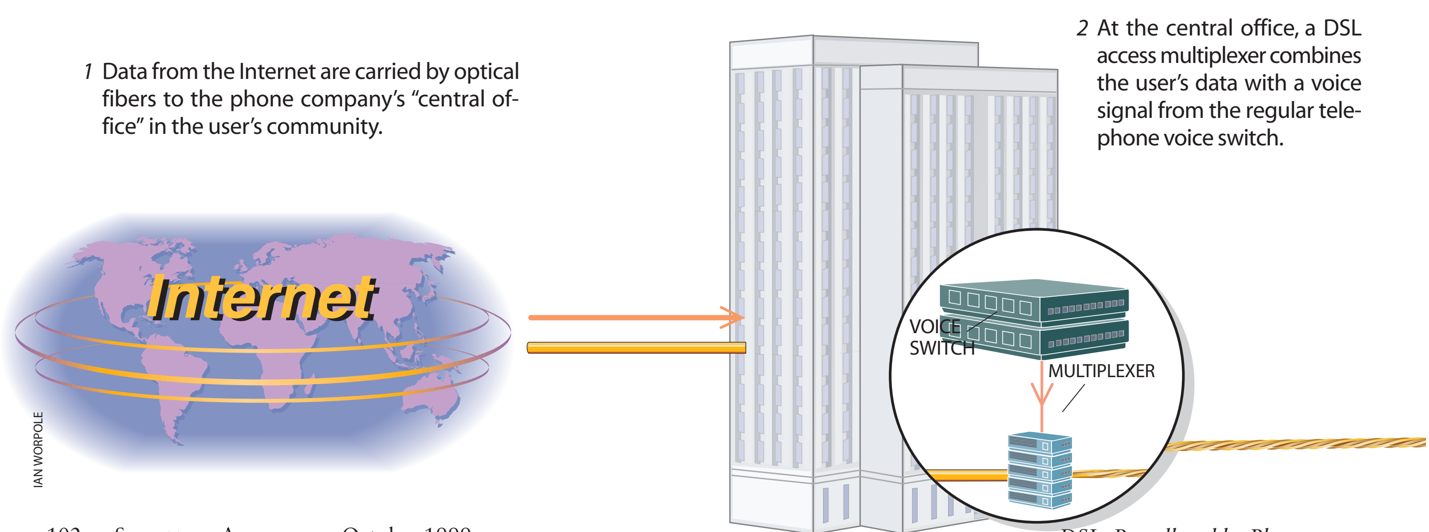
The capacity of a communications channel depends on its bandwidth (the range of frequencies it uses) and its signal-to-noise ratio (which depends on the quality of the connection). Once those are fixed, it is physically impossible to exceed the fundamental limit that renowned Bell Labs scientist Claude E. Shannon spelled out in 1948. A voice connection through a conventional phone network uses a bandwidth of about 3,000 hertz (Hz): from about 300 Hz to 3,300 Hz. An analog modem operating at 33.6 kilobits per second (kbps) requires a slightly wider bandwidth—3,200 Hz—and needs a very good connection, one with a high signal-to-noise ratio. Shannon's formula tells us that such a modem is very close to the channel's theoretical capacity, about 35 kbps, a feat that has taken 30 years of modem circuit development. Modems operating at 56 kbps achieve their rates by taking advantage of digital connections that circumvent some sources of noise in transmissions toward the end user. (They are still limited to 33.6 kbps for signals sent toward the service provider by the end user.)

But these bit rates are far from the maximum possible on a twisted pair alone. One process that limits bandwidth and signal strength is the steady attenuation of the signal as it travels down the line, with the higher frequencies being affected more severely. Greater capacity is therefore available if the lines are kept short.

Joseph W. Lechleider, an engineer recently retired from Telcordia (previously Bellcore), proposed in the 1980s using an ordinary phone line as a very high bandwidth channel, over the short distance from the end user to a telephone central office. He also proposed multilevel coding of the signal to further enhance performance. This transmission technique was dubbed the digital subscriber line. By the early 1990s, several firms, led by California-based PairGain Technologies, had developed "high-bit-rate" flavors of DSL (known as HDSL) that could transmit almost 800 kbps over a distance of four kilometers.

Concurrent with the development of symmetric HDSL, John Cioffi of Stanford University demonstrated a signal coding technique called Discrete Multitone, using it to send more than eight million ("mega-") bits per second through a tele-

How ADSL Sends Broadband Data and Voice over a Phone Line



Alexander Graham Bell's ubiquitous copper wires will still be a capacity-rich communications resource in the third millennium

phone pair more than 1.6 kilometers in length. The technique divides an overall bandwidth of about 1 MHz into 256 subchannels of about 4 kHz each. In essence, it creates 256 virtual modems operating simultaneously over the same line.

Originally, the Discrete Multitone approach was intended for sending entertainment video over telephone wires. Because such use relies principally on one-way transmission, most of the subchannels were devoted to the "downstream" signal (flowing toward the consumer), carrying about 6 Mbps, with about 0.6 Mbps available in the other direction. This asymmetric form of DSL has become known as ADSL, and the signal coding is now a worldwide standard.

Although the video application has not yet borne fruit, asymmetric transmission fortuitously lends itself to browsing on the World Wide Web. Over the past year ADSL has begun to be widely installed in telephone networks for always-on Internet access, typically operating at several hundreds of kbps or higher over phone wires up to about 5.5 kilometers in length. The beauty of ADSL, unlike the multilevel coding used in HDSL, is that the data can use channels operating above the voice frequency band, so a single phone line can simultaneously transmit voice and high-speed data.

The future of ADSL for the masses lies with G.lite, a global standard that limits the data rates to 1.5 Mbps downstream to the consumer and about 0.5 Mbps upstream. Truncating the speed lets G.lite operate reliably on more than 70 percent of unaltered phone lines and lowers costs and power consumption. Home computers containing G.lite-ready circuitry are already being sold.

ADSL has a number of advantages over systems that use a cable television network. With ADSL the signal on your line is not shared with other users. Cable modems work over what amounts to a giant party line: when someone else is receiving data, you can't—although you (and everyone else) can listen in on their data signal, albeit without the key to decode it, if it is encrypted. Telephone wires, on the other hand, are physically secure.

The backbone networks for ADSL carry composite signals for a few hundred consumers at 155 Mbps and up. A television channel has an effective throughput of only about 24 Mbps, greatly limiting its effectiveness under heavy use by hundreds of cable modems. The ADSL traffic also benefits from a statistical economy of scale—for example, 1,550 people sharing a backbone of 155 Mbps will experience better performance than 240 sharing 24 Mbps.

Although cable networks cover 90 percent of the homes in the U.S., they do not serve many businesses. Telephone networks are ubiquitous. Moreover, for effective use of cable modems the cable operator must invest billions to upgrade the cable network with fiber optics and two-way transmission equipment; ADSL, on the other hand, takes advantage of the same kind of telephone pairs that Alexander Graham Bell used in the 19th century.

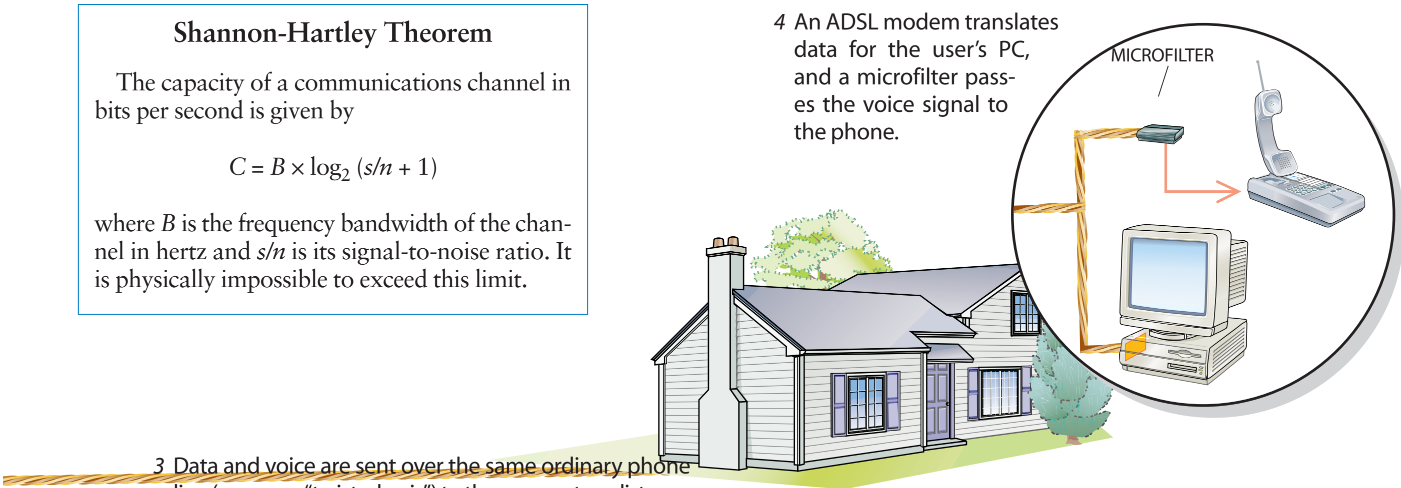
Cable modems have a roughly two-year head start on DSL. It's not enough. Projections show that the number of DSL users will surpass those of cable modems within the next year or so. There is still plenty of life—and capacity—left in the old copper phone line.

Shannon-Hartley Theorem

The capacity of a communications channel in bits per second is given by

$$C = B \times \log_2 (s/n + 1)$$

where B is the frequency bandwidth of the channel in hertz and s/n is its signal-to-noise ratio. It is physically impossible to exceed this limit.



4 An ADSL modem translates data for the user's PC, and a microfilter passes the voice signal to the phone.

3 Data and voice are sent over the same ordinary phone line (a copper "twisted pair") to the user, up to a distance of five to six kilometers, depending on line quality.

The Broadest Broadband

by Paul W. Shumate, Jr.

Optical fiber has successfully replaced metallic cables in the backbone networks of most local and long-distance telephone carriers, cable television operators and utility companies. So why not extend lines of optical fiber all the way to customers' homes? Doing so would eliminate the so-called last-mile bottleneck that restricts users' access to the Internet and other services. In current fiber-to-the-home systems, customers can download data at up to 100 million bits per second (future fiber networks may perform much more quickly), which is at least 10 times faster than transmissions using metallic cables today. The capacity of optical fiber is so enormous that it can handle all types of communications signals simultaneously; for example, telephone, television, videoconferencing, movies-on-demand, telecommuting and Internet traffic could all be carried together on one user's fiber.

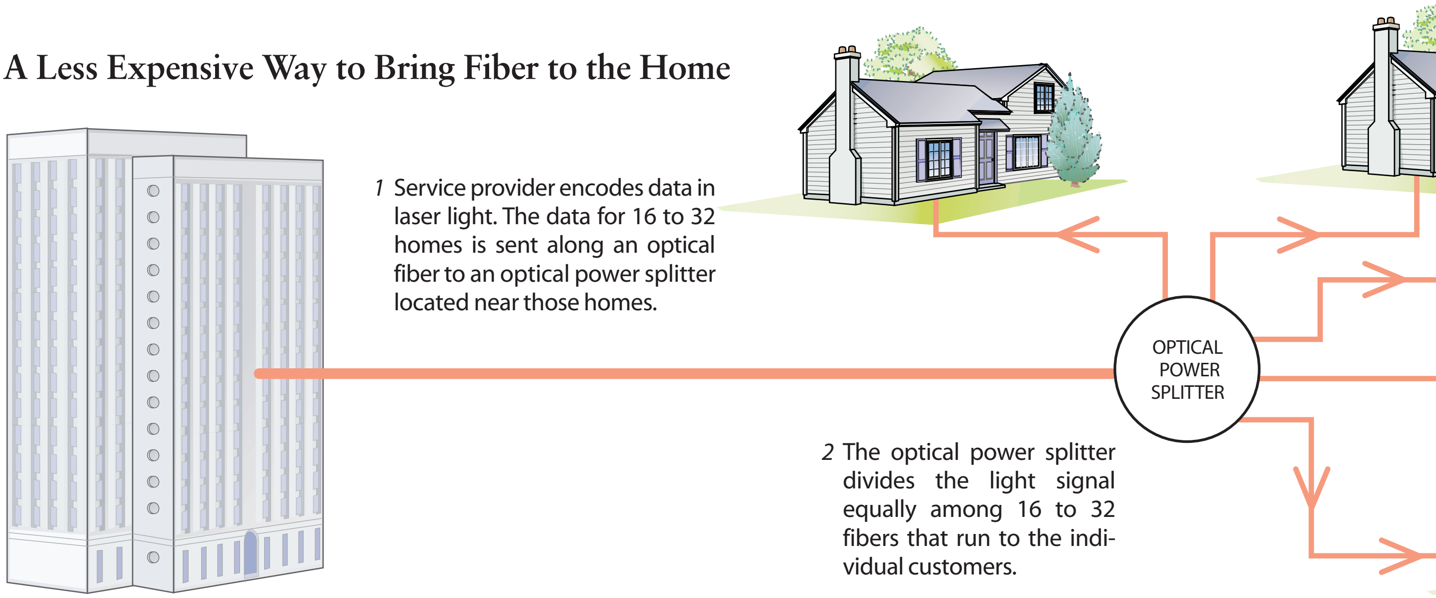
Until recently, the major obstacle to fiber-to-the-home has been its high cost. Dedicating one or two lines of fiber to each customer, along with the electronics needed at each end to transmit and receive the optical signals, is very expensive. For a typical suburban home, the one-time installation cost—including the cost of all the equipment—is currently about $1,500. (Approximately half is attributable to the electronics.) This figure has dropped from about $5,000 a decade ago and is continuing to fall as fiber technology advances. But it is still higher, in most cases, than the cost of connecting a comparable home with metallic cable.

Because backbone networks are highly multiplexed—that is, a single fiber in the network can carry many independent channels of signals—the cost per channel is relatively low. Therefore, telephone and cable TV companies take advantage of fiber's astounding capacity by installing it partway to homes. In these systems, often called fiber-to-the-node, fiber-to-the-cabinet or fiber-to-the-curb, a few fibers connect a service provider to an enclosure near a group of homes. This enclosure holds the equipment for converting the optical signal in the fiber to an electrical signal that can travel on metallic cables. The metallic connections to the homes vary in distance from less than 30 meters (100 feet) to slightly more than one kilometer. Such systems are economical because they share the cost of the fiber and electronics among all the subscribers in the group, who can number in the hundreds. The transmission rates, however, are lower than those of fiber-to-the-home, because the final metallic connections act as bottlenecks.

Networks of Light

Fiber-to-the-home has been technically successful in more than three dozen field trials and installations worldwide; the earliest was in Higashi-Ikoma, Japan, in 1977. Now it is becoming commercially viable, thanks to recent advances in architectures and technologies. The first important change was the development of the passive optical network, or PON, in which a single fiber extends from an optical transceiver at the service provider's location to an optical splitter near a small group of homes. The splitter divides the light signals equally among 16 or 32 output fibers, which then carry the signals to the customers' homes. In 1998 the International Telecommu-

A Less Expensive Way to Bring Fiber to the Home



New technologies promise to reduce the cost of linking homes with optical fiber, the ultimate medium for data communications

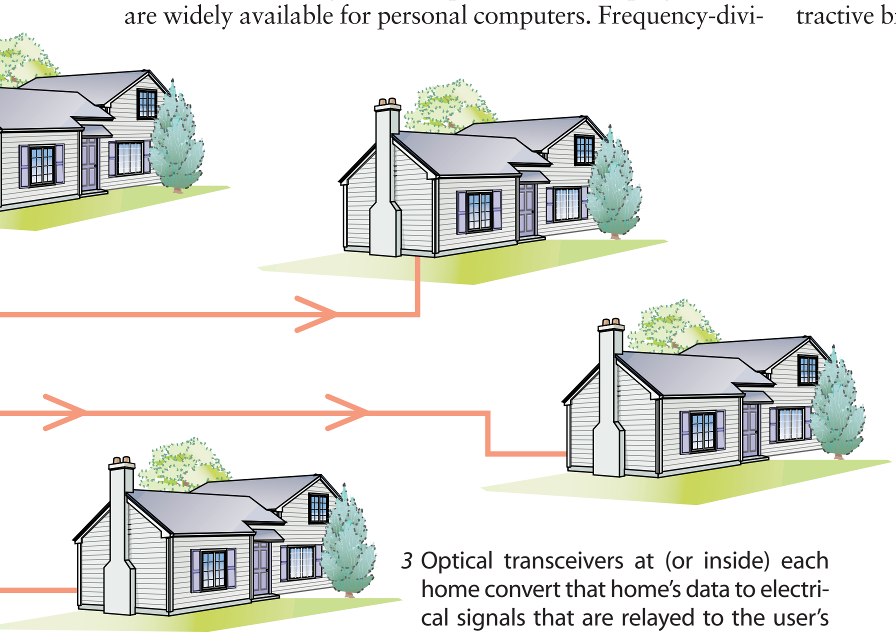
nication Union (ITU) standardized the specifications for such networks. PONs are less expensive than earlier fiber-to-the-home systems because they do not require the installation of an optical transceiver and a full-length fiber for each customer. Other factors making fiber-to-the-home less costly include new lasers, optical components, fiber cables and digital integrated circuits designed specifically for the application.

Distance isn't as important with fiber as it is with copper cables, because optical signals lose very little power as they move through fiber. PONs work as well in rural areas, where homes are widely separated, as they do in suburban or urban settings. The network does entail equipment and installation costs that are not fully shared by the customers, such as the expense of the final length of fiber from the splitter to the home and of the terminal in the home where the optical/electrical conversions take place. A group of manufacturers, though, has outlined a strategy for aggressively reducing those costs over the next few years.

In these optical networks, a primary challenge is to organize the digital traffic so that a single fiber can simultaneously accommodate different types of signals. Voice and video, for example, require nearly constant data rates, whereas file transfers and e-mail can be transmitted in intermittent streams. Several techniques are used to pack all these signals into the available bandwidth. The ITU-specified network uses asynchronous transfer mode, which has been designed to handle such a mix of data efficiently. An older protocol called Ethernet has the advantage that inexpensive Ethernet plug-in cards are widely available for personal computers. Frequency-division multiplexing creates many channels in a single fiber by modulating the light at a different frequency for each channel. The most advanced PONs will employ wavelength-division multiplexing, which assigns a unique wavelength, or color, of light for each customer's signal. Most wavelength-multiplexing devices are now expensive, but costs will fall rapidly because the technique is commonly used in backbone networks.

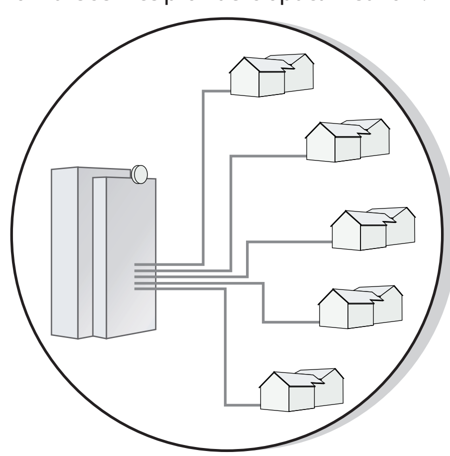
Although a few fiber-to-the-home systems dating from the trials of the 1980s and early 1990s remain in operation, the telecommunications industry's focus is now on the newer technologies. Passive optical networks have been tested in England, France, Belgium, Bermuda and Japan. BellSouth and NTT—Japan's largest telecommunications company—are planning to install products compliant with the ITU standard later this year. Frequency-division multiplexed fiber systems are operating in several rural communities in the Midwest, providing telephone, television and Internet services. In rural areas, fiber-to-the-home appears to be more economical than conventional networks are, regardless of the type of multiplexing used.

With the introduction of inexpensive standardized products, many businesses are reconsidering the advantages of fiber-to-the-home. The demand for high-speed digital services is sure to grow, which means that customers will be clamoring for systems that can cheaply deliver extraordinary amounts of data. Optical fiber can transmit more data than any other medium on the market, and the cost of connecting it to homes is dropping rapidly. So in the coming years more and more customers will decide that fiber-to-the-home is the most attractive broadband option. SA



3 Optical transceivers at (or inside) each home convert that home's data to electrical signals that are relayed to the user's computer and other devices.

In an older and more expensive scheme, each home had its own fiber installed all the way from the service provider's optical network.



IAN WORPOLE

Satellites: The Strategic High Ground

by Robert P. Norcross

If you want to see the future of broadband communications, look to the stars. The heavens could soon be filled with more than 400 satellites providing Internet users with low-cost, direct-to-the-home connections that are hundreds of times faster than today's dial-up modems. With unobstructed views of virtually the entire world, satellites are poised to deliver interactive broadband services in ways even advanced ground-based networks will be hard-pressed to match.

The new breed of satellites will act as powerful signal repeaters in the sky, receiving and resending radio transmissions from ground-based antennas. Costing far less per unit capacity than most satellites now in service, they will employ new digital technologies that will improve the capacity, reliability and security of data communications. Moreover, because the systems will operate at extremely high radio frequencies, they will use narrow radio beams capable of communicating with ultrasmall antennas that can be easily mounted on most homes.

Broadband Systems in the Sky

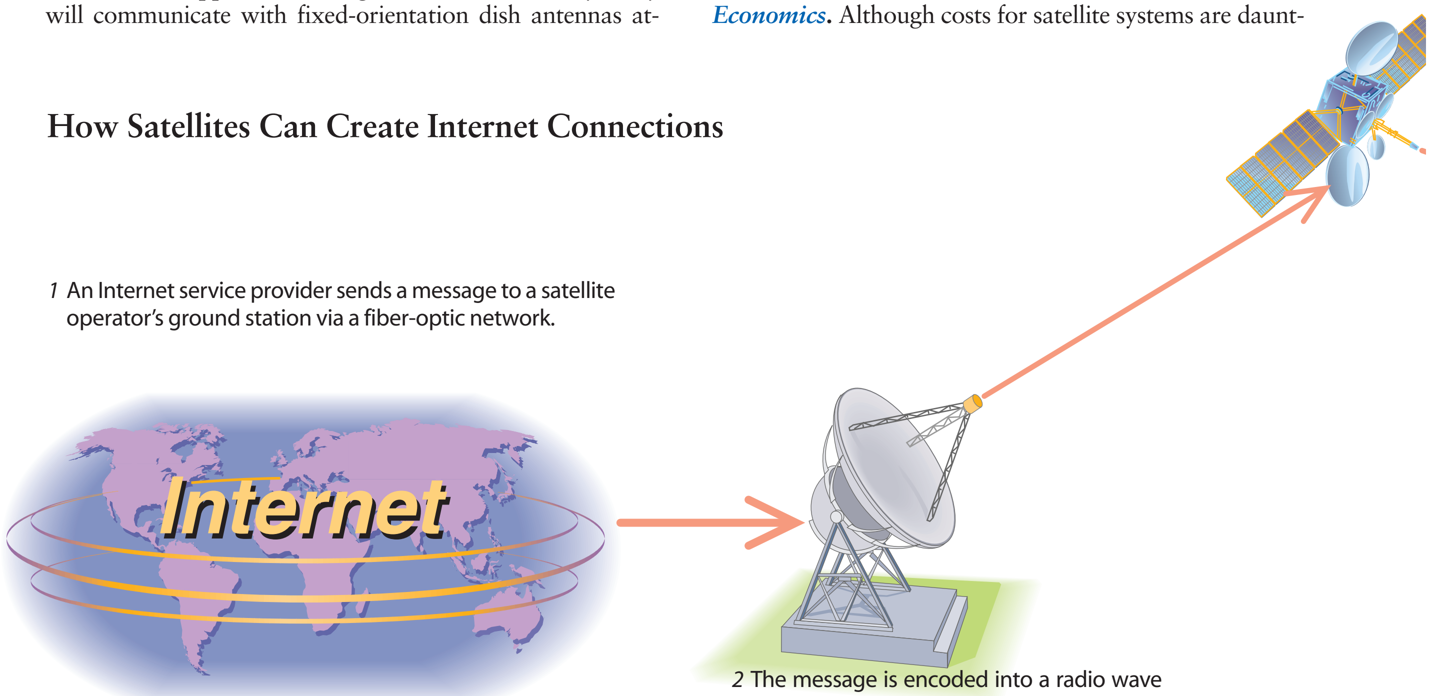
Two types of satellite systems have been proposed. Geostationary satellites will orbit 36,000 kilometers (22,000 miles) above the equator at the same speed as the earth's rotation and thus appear from the ground to be stationary. They will communicate with fixed-orientation dish antennas attached to customers' homes and use advanced signal processing to compensate for transmission delays caused by the great distances their radio signals must travel. Low-earth orbit (LEO) satellites, in contrast, will circle the globe once every two hours at altitudes under 1,500 kilometers, reducing the time needed to beam signals to and from the earth's surface. But they will require sophisticated subscriber antennas able to track and communicate with the fast-moving LEO satellites.

Both types of satellites will avoid many of the complications that plague ground-based networks. Specific advantages include the following:

Ubiquity. The dirty little secret of broadband is that the technical limitations of ground-based networks will severely restrict their availability. Digital subscriber line (DSL) signals decay on long telephone lines or on those of poor quality. Local multipoint distribution service (LMDS) signals cannot penetrate leafy trees, buildings or other obstructions. Cable performance deteriorates if too many households in a neighborhood log on at the same time. Fiber-to-the-home is so costly as a retrofit that it is usually considered economically viable only for new housing construction. For up to one third of the population in the U.S. and an even greater portion worldwide, satellite technology will not simply be *a* choice, it will be *the* choice.

Economics. Although costs for satellite systems are daunt-

How Satellites Can Create Internet Connections



1 An Internet service provider sends a message to a satellite operator's ground station via a fiber-optic network.

2 The message is encoded into a radio wave and beamed to satellites overhead.

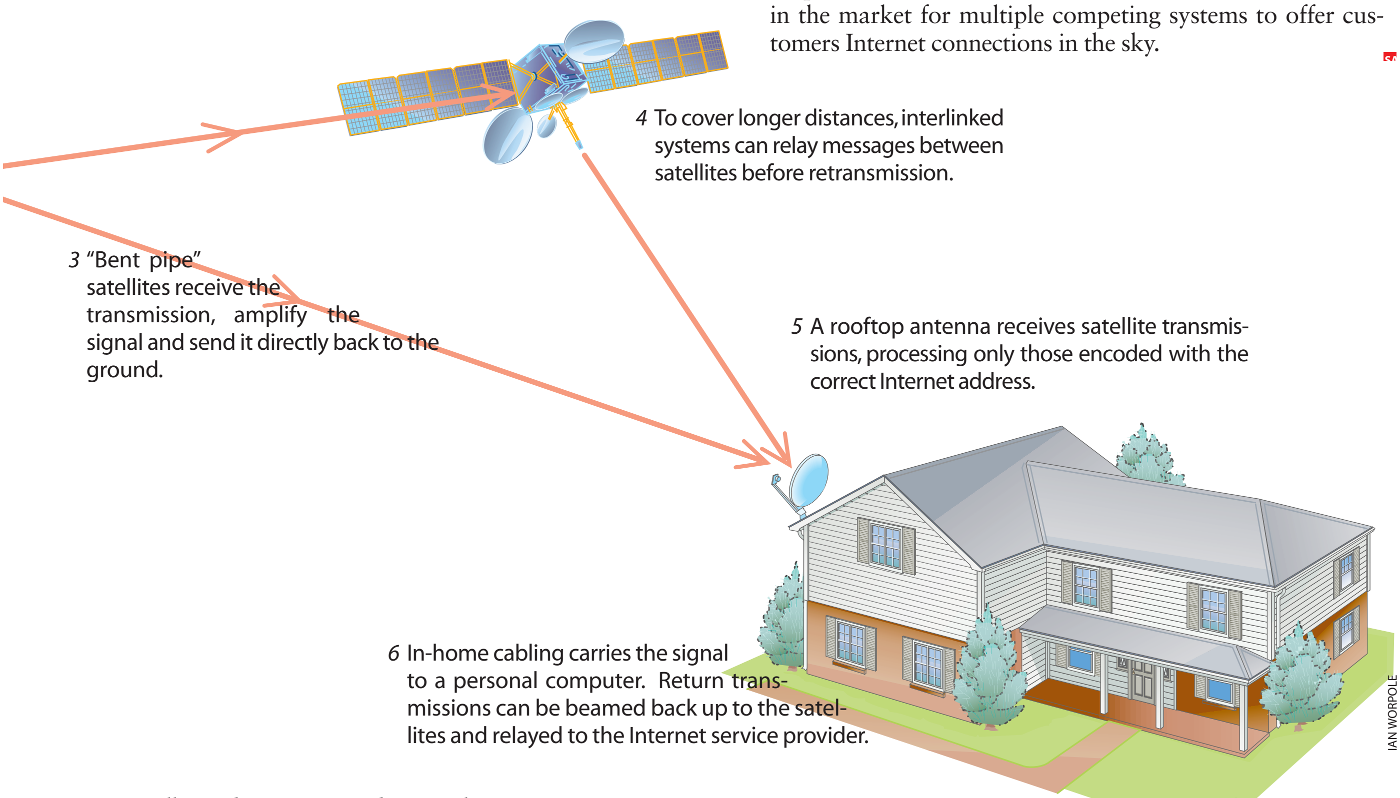
Data communications systems that use satellites to transmit signals have many advantages over ground-based systems

ing—estimates range from $4 billion to more than $10 billion for global systems—their capabilities are even more impressive. The combined capacity of proposed broadband satellite systems would in theory be sufficient to handle all the world's voice communications several times over. In addition, satellites can dynamically allocate transmission capacity among subscribers to ensure it is available where and when needed. This improves the satellites' efficiency so much that a single system will be able to accommodate tens of millions of subscribers—thus reducing the system's cost to only a few hundred dollars per customer. (Each customer would also have to pay an estimated $500 to $1,000 for the rooftop antenna.)

Performance. In the bits-per-second race, satellites win hands down over all options except the much more expensive fiber-to-the-home. Research shows that broadband subscribers value high data transmission rates over other service attributes, and their "need for speed" more than doubles every year as Internet Web sites become more elaborate and data-intensive. Satellites are well positioned to serve this burgeoning demand for rapid Internet downloads, with maximum transmission speeds twice as fast as LMDS, three to six times faster than cable modems, and up to 12 times faster than DSL.

Competitive diversity. Although discussions of broadband communications tend to focus on technological and economic issues, the most important driver behind satellite services may well be the competitive aspirations of large, powerful telecommunications companies. There are simply more firms planning to market broadband services than there will be ground-based broadband networks available. Telecommunications companies that do not own and cannot buy telephone or cable networks in areas where they wish to operate will have to seek out other options, and satellites are uniquely capable of serving their needs.

Despite such obvious advantages, satellites receive scant attention compared with ground-based broadband options. This may reflect the telecommunications industry's discomfort with new satellite technologies or a bias for ground-based solutions to meet its future needs. Nevertheless, several companies are moving beyond the design stage and have announced plans to launch satellite systems in 2002, with broadband Internet services becoming available the next year. With market analysts expecting satellites to serve 15 to 20 percent of broadband subscribers, there should be room in the market for multiple competing systems to offer customers Internet connections in the sky.



LMDS: Broadband Wireless Access

by John Skoro

The past decade has seen explosive innovation by the telecommunications industry as it strives to satisfy a worldwide appetite for greater bandwidth. Several developments are fueling this growth—the proliferation of the Internet, increased dependence on data and a global trend toward deregulation of the industry.

Nowhere is the phenomenon more evident than in the quest to alleviate the local-loop bottleneck. This constriction occurs where local-area networks, which link devices within a building or a campus, join to wide-area networks, which criss-cross countries and hold the Internet together.

Advances in fiber technology have extended the capacity of wide-area networks to trillions of bits per second. Meanwhile local-area networks are evolving from 10 megabits per second (Mbps) to gigabits per second. The connections between these two domains have not kept pace, the vast majority of copper-wire circuits being limited to about the 1.5 Mbps rate of a so-called T1 line. The typical home user faces a more extreme case of the same affliction, with data crawling between computer and Internet about 30 times slower, through a modem and phone line operating at a mere 56 kilobits per second (kbps).

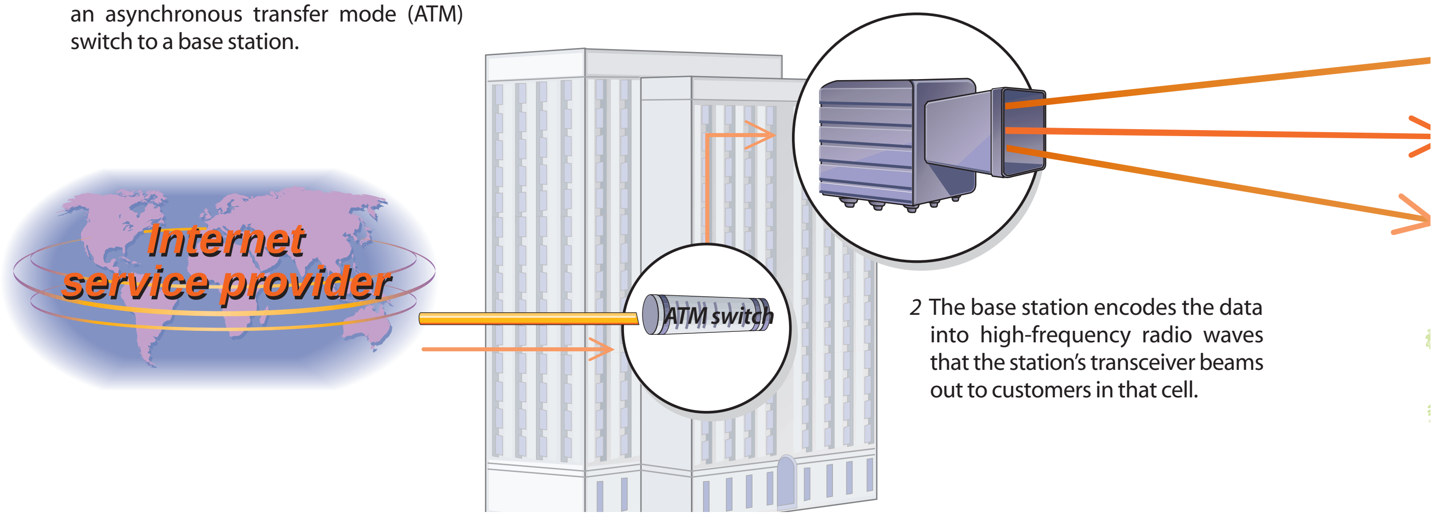
Of the variety of technologies developed for high-speed wireless access, local multipoint distribution service (LMDS) offers an ideal way to break through the local-access bottleneck. Like cell phone networks, LMDS is a wireless system but is designed to deliver data through the air at rates of up to 155 Mbps (typical cell phone voice calls use a mere 64 kbps, or 8 kbps in compressed digital systems). LMDS may be the key to bringing multimedia data to millions of customers worldwide. It supports voice connections, the Internet, videoconferencing, interactive gaming, video streaming and other high-speed data applications.

A major advantage of LMDS technology is that it can be deployed quickly and relatively inexpensively. New market entrants who do not have the luxury of an existing network, such as the copper wires or fiber of incumbent operators, can rapidly build an advanced wireless network and start competing. LMDS is also attractive to incumbent operators who need to complement or expand existing networks. For example, operators who are setting up a service primarily based on digital subscriber lines but who want their service to be universally available could use LMDS to fill in gaps in their coverage. And while cable modems are making inroads in the residential and home-office markets, the business market (where little to no cable network exists) remains a prime niche for LMDS.

The higher capacity of LMDS is possible because it operates in a large, previously unallocated expanse of the electromag-

How a Wireless System Can Send Broadband Data through the Air

1 Data from the Internet service provider travel over a fiber-optic network, through an asynchronous transfer mode (ATM) switch to a base station.



2 The base station encodes the data into high-frequency radio waves that the station's transceiver beams out to customers in that cell.

Ground-based wireless networks delivering the full range of broadband services can be deployed quickly and inexpensively

netic spectrum. In the U.S. the Federal Communications Commission has auctioned to LMDS operators a total bandwidth of about 1.3 gigahertz (GHz) in the "millimeter" waveband at frequencies of about 28 GHz. In other countries, depending on the local licensing regulations, broadband wireless systems operate at anywhere from 2 to 42 GHz. Canada, which is actively setting up systems around the country, has 3 GHz of spectrum set aside for local multipoint communications systems, as it is called there. Regular digital cell phone systems operate at about 0.8 GHz with a typical bandwidth allocation of 30 MHz or less.

How It Works

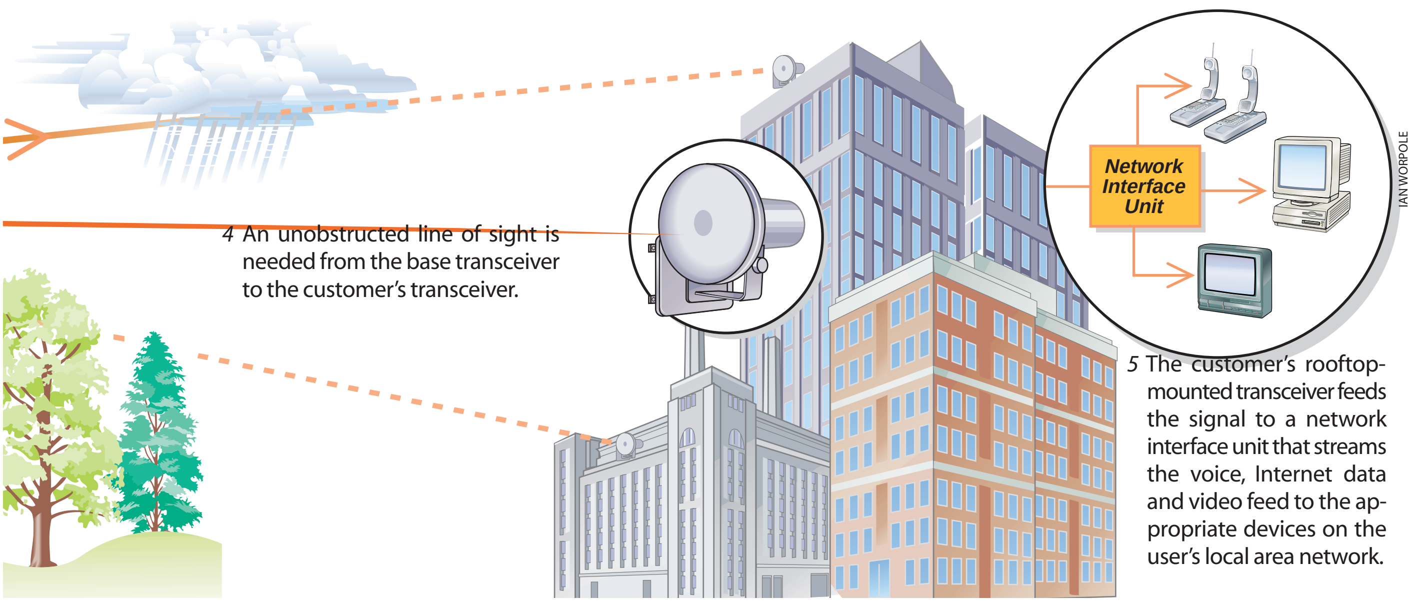
Sending digital signals of the required complexity at 28 GHz is made practical by recent improvements in the cost and performance of technologies such as digital signal processors, advanced modulation systems and gallium arsenide integrated circuits, which are cheaper and function much better than silicon chips at these high frequencies.

LMDS uses wireless cells that cover geographic areas typically from two to five kilometers in radius. Unlike a mobile phone, which a user can move from cell to cell, the transceiver of an LMDS customer has a fixed location and remains within a single cell. A common design puts the customers' antennas on rooftops, to get a good line of sight to the hub transceiver.

The LMDS cell size is limited by "rain fade"—distortions of the signal caused by raindrops scattering and absorbing the millimeter waves by the same process that heats food in a microwave oven. Also, walls, hills and even leafy trees block, reflect and distort the signal, creating significant shadow areas for a single transmitter. Some operators have proposed serving each cell with several transmitters to increase coverage; most will have one transmitter per cell, sited to target as many users as possible. Of value to operators, in an industry with a high rate of turnover of customers, is the ability to pick up the hub equipment and move it to a different location, as market economics dictates—an impossibility with networks of telephone wires, television cable and optical fiber.

Most, if not all, LMDS systems send data using a technique called asynchronous transfer mode, which is used extensively in wide-area networks and allows a mixture of data types to be interleaved. Thus, a high-quality voice service can run concurrently over the same data stream as Internet, data and video applications. In summary, LMDS will be a versatile, cost-effective option for both providers and users of broadband services, with the rapid and inexpensive deployment being particularly attractive to the providers.

3 The size of the cell is limited by "rain fade."



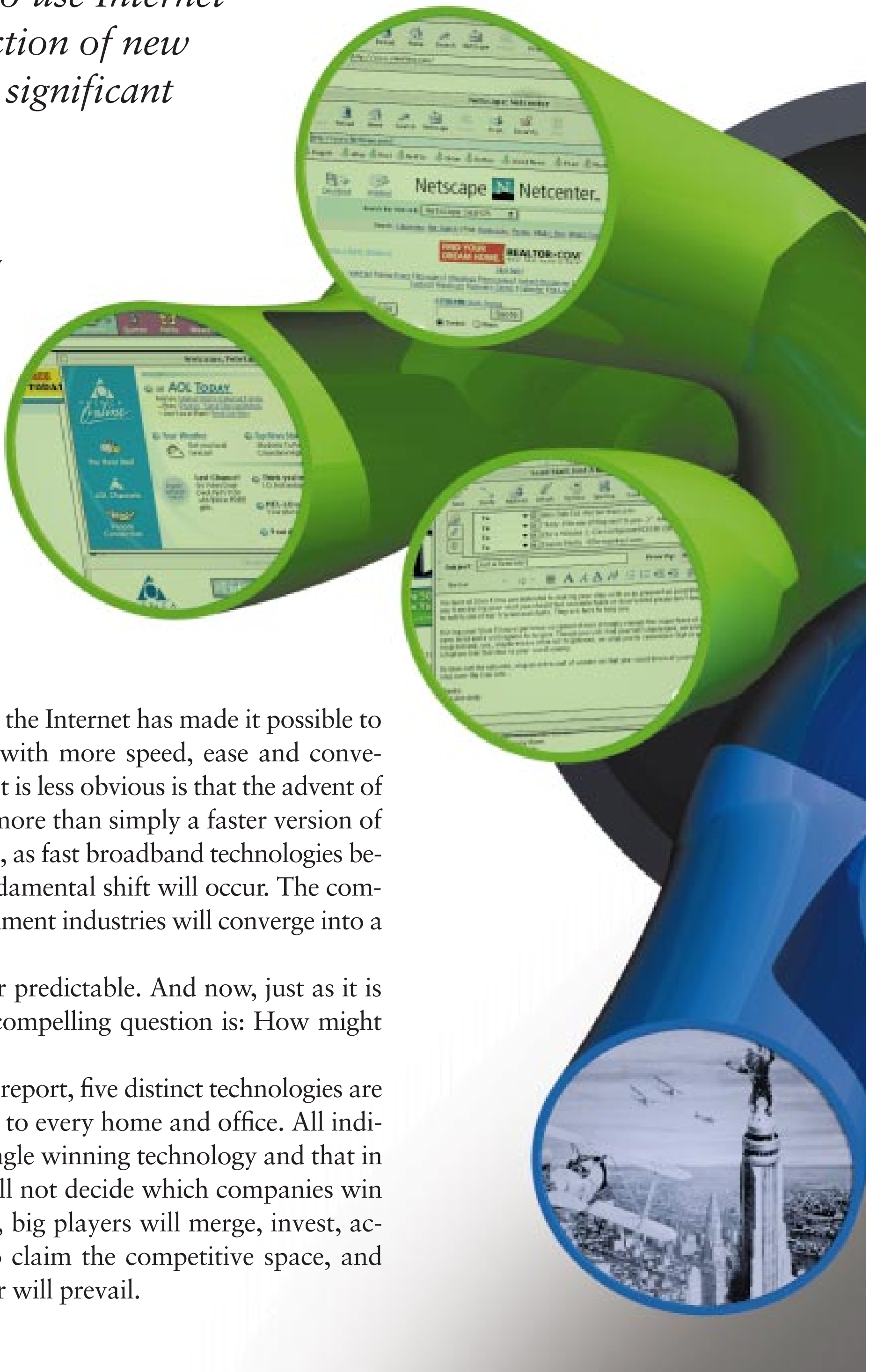
4 An unobstructed line of sight is needed from the base transceiver to the customer's transceiver.

5 The customer's rooftop-mounted transceiver feeds the signal to a network interface unit that streams the voice, Internet data and video feed to the appropriate devices on the user's local area network.

THE LIGHT at the End of the Pipe

A much faster and easier-to-use Internet will stimulate the introduction of new services and possibly even significant social metamorphoses

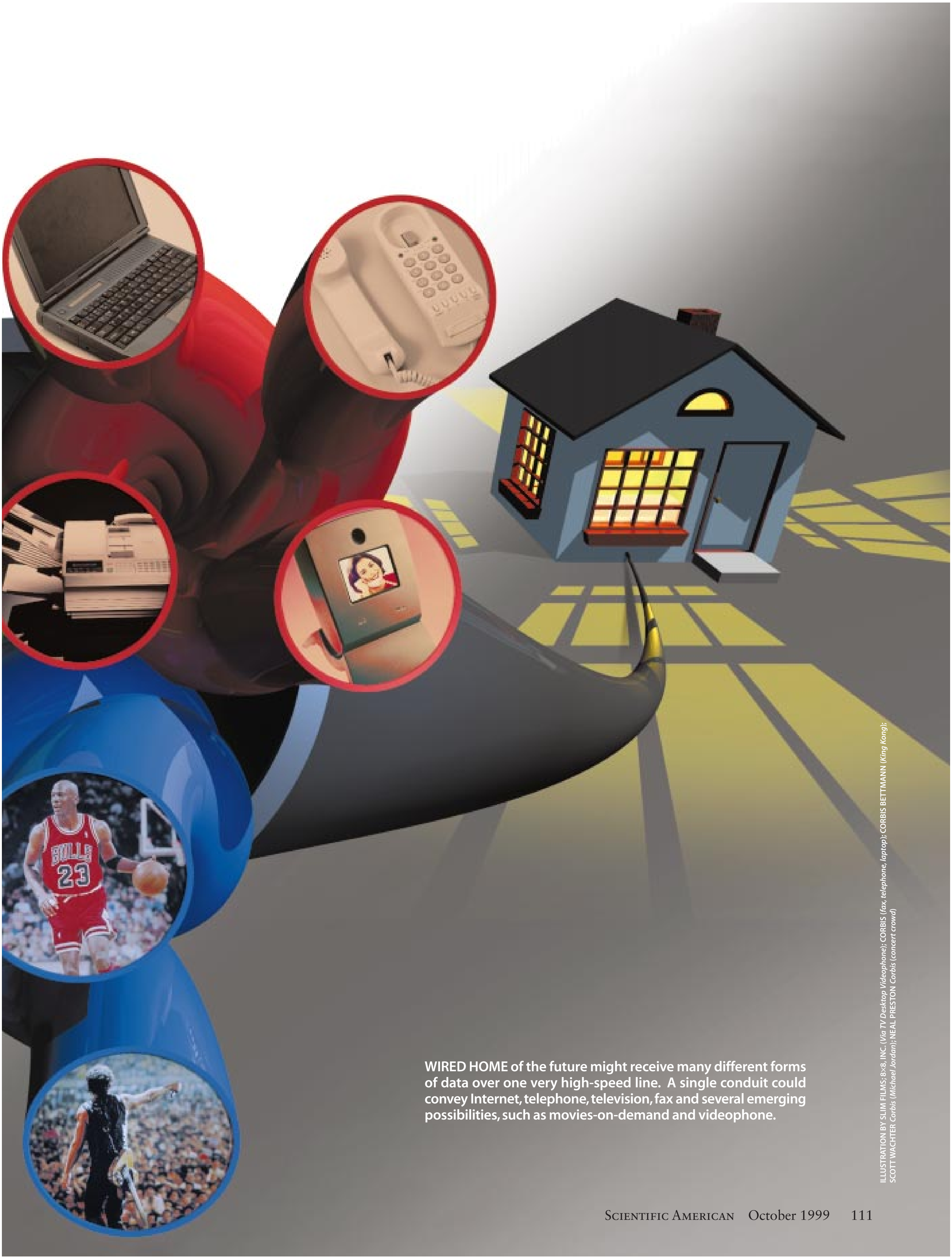
by P. William Bane and Stephen P. Bradley



The big picture is well known: the Internet has made it possible to swap digitized information with more speed, ease and convenience than ever before. What is less obvious is that the advent of much higher speed links will bring us more than simply a faster version of the Internet. Over the next several years, as fast broadband technologies begin pervading the Internet, a more fundamental shift will occur. The communications, information and entertainment industries will converge into a single, sprawling business.

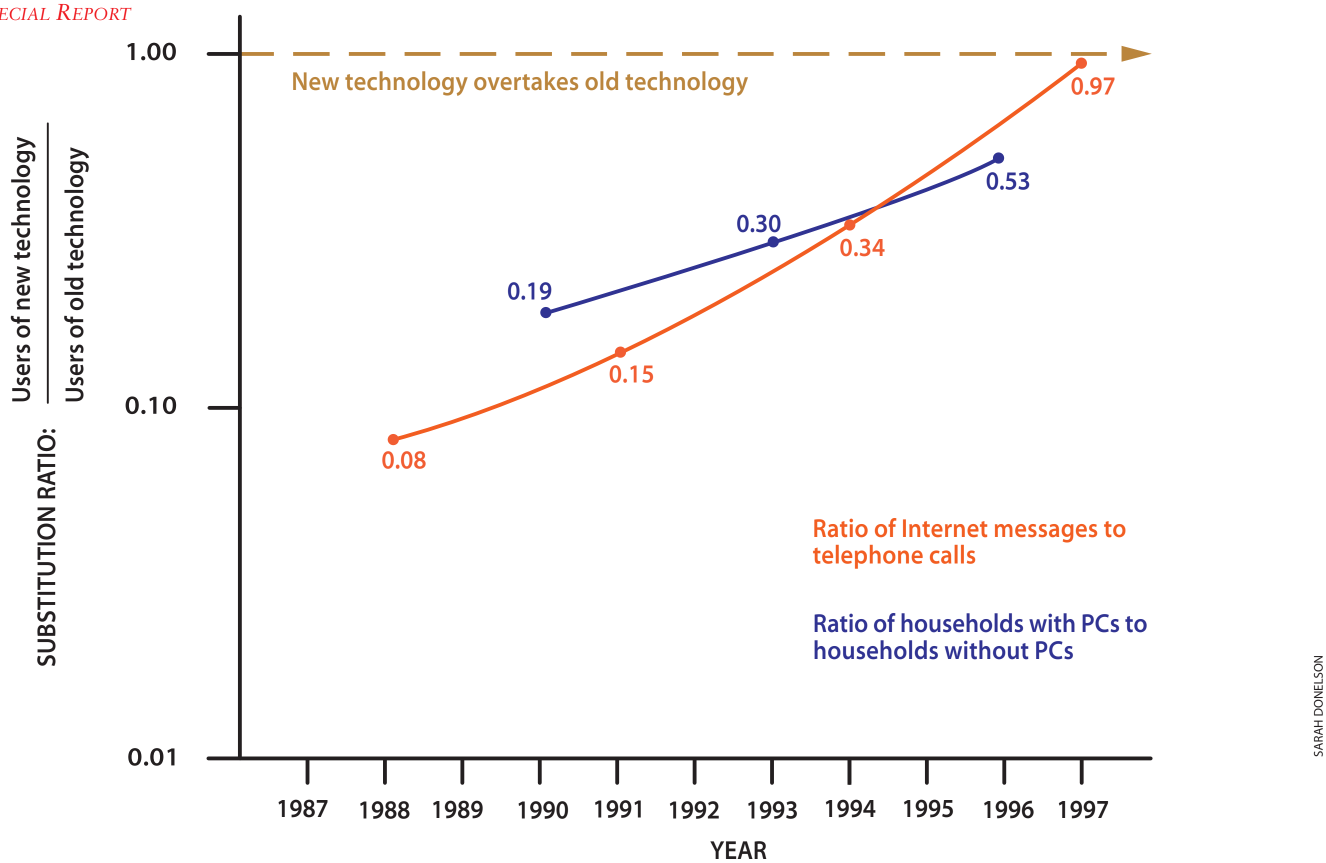
This transition will not be smooth or predictable. And now, just as it is getting under way, perhaps the most compelling question is: How might broadband affect our lives?

As described elsewhere in this special report, five distinct technologies are candidates to bring broadband service to every home and office. All indications suggest that there will be no single winning technology and that in any event technological superiority will not decide which companies win or lose. Over the next five years or so, big players will merge, invest, acquire and merge again in attempts to claim the competitive space, and whatever technologies these firms favor will prevail.



WIRED HOME of the future might receive many different forms of data over one very high-speed line. A single conduit could convey Internet, telephone, television, fax and several emerging possibilities, such as movies-on-demand and videophone.

ILLUSTRATION BY SLIM FILMS; 8×8, INC. (*Via TV Desktop Videophone*); CORBIS (*fax, telephone, laptop*); CORBIS BETTMANN (*King Kong*); SCOTT WACHTER *Corbis* (*Michael Jordan*); NEAL PRESTON *Corbis* (*concert crowd*)



E-MAIL MESSAGES are replacing telephone calls at a rate greater than that at which households are acquiring personal computers. The broken line at the top of the graph indicates where the ratios equal one; historically, reaching such an inflection point portends major consequences. The data in this graph were collected from various sources by Mercer Management Consulting in Washington, D.C.

The most interesting promise of broadband, however, lies beyond its merely becoming a faster, cheaper telephone-television-Internet system. For major parts of the economy to be transformed or even just "roughed up" by the Internet, useful and bona fide new services will have to materialize. Whether and when such benefits take shape will determine how pervasive broadband becomes and how much consumers will pay for its high-speed data transmission and "always-on" connectivity.

How Much Do You Want It?

Do people really want broadband? All our experience with the Internet suggests that they do. Today's Internet is a kind of broadband on training wheels. Even in its current, nascent stage, it has successfully engaged consumers, unleashed creative forces within enterprises and connected previously disparate individuals into virtual communities. The rate of adoption has been unprecedented: five years ago less than 1 percent of U.S. households were on-line; now one third of them are, representing 50 million people. In contrast, it took radio 38 years, telephone 36 years, television 13 years and cable TV 10 years to achieve similar levels of penetration.

Now the Internet is poised to exert an even greater influence. Messages sent via the Internet Protocol (IP)—primarily e-mail—are increasingly replacing traditional phone and fax communication. The number of IP messages in any given period now equals the number of phone and fax messages, implying a substitution ratio of 1.0 [*see illustration above*]. History shows that there are major consequences when such inflection points are reached. Consider when plastics replaced paper and metal as packaging; one of the unforeseen results was the advent of take-out meals and of the fast-food industry, which widely altered home-cooking and home-life patterns. The onset of inexpensive air travel diminished the share of the transportation market of sea, rail and even some auto travel, with ramifications for commerce, population distributions and regional cultures.

Broadband will continue to drive Internet substitution for older forms of communication. A May 1999 survey by Mercer Management Consulting in Washington, D.C., where one of the authors (Bane) works, showed that people with high-speed access search for information and make purchases online at approximately double the rate of those with lower-speed analog modems [*see illustration on page 114*]. The survey was of roughly 1,000 users who access the Internet via cable modems.

Those with high-speed access to the Internet are a minority now. But three forces are combining to accelerate broadband's replacement of narrowband: the price of a certain level of performance; response time; and network effects.

Of course, lower prices have raised demand for almost all electronic services in the past. When America Online introduced flat-rate pricing in December 1996, the on-line time per individual shot up; no longer charged on a per-minute basis, people would log on and stay on even while not using the Internet or checking e-mail. The process is not gradual: little happens until a threshold price is reached, which then triggers a burst of new demand. Broadband now appears to be nearing its threshold, making it likely that we will soon see additional dramatic price performance improvements and consequent leaps in demand.

Broadband will also create faster access and response time, further stimulating Internet use. Simply stated, most people will not use the Internet frequently and for a wide variety of tasks until they have the high-speed and always-on characteristics of most broadband services.

Finally, and most important, as a network expands it becomes exponentially more valuable to each and every user. A physical mail or e-mail system that reaches 99 percent of addresses is far more than twice as useful as one that reaches 50 percent of addresses. Today's low-bandwidth computers and telephones connect users with one another but only in mildly useful interactions. The setup is like a dog walking on its hind legs. As the old saying goes: the animal does not do it well, but it is amazing that it does it at all. To continue the analogy, broadband—with more offerings, more users and vastly more useful interactivity—is like a greyhound running on all fours.

Creating Social Utility

Low price, high speed and constant availability will undoubtedly accelerate the growth of electronic commerce and of on-line communities. But before consumers will embrace broadband communications—and pay more for it than they would for plain old telephone, TV or Internet service—the system has to offer something more.

That something is greater social utility—the enjoyment or fulfillment people derive from consuming a good or utilizing a service. We can't predict exactly what new goods and services will ultimately emerge, but they will all have to provide three key dimensions of social utility: choice and pleasure, efficient consumption, and financial payback.

The first category, choice and pleasure, actually has to do with the limited amount of leisure time most people have. Because that time is essentially fixed, new forms of communication and entertainment will thrive only by displacing existing forms. Indeed, the Internet has already begun to encroach on time spent viewing TV and movies (as well as sleeping). If new offerings are to continue stealing time from old ones, they will have to give users greater control over the form and timing of communication and entertainment. Greater choice brings more options and thus increases the chance for greater pleasure. Better tools that find more possibilities and advice—even when people don't know what to ask for—will help.

Efficient consumption addresses the significant fraction of an individual's personal time spent on overhead tasks such as reading junk mail, paying bills, filling out order forms, waiting for appointments, preparing tax returns and so on. Broadband will unleash value if it can automate many of these processes, raising the efficiency of consumption. Shopping for a gift, for instance, means finding the best option, given your available cash and search time. The Internet makes it possible not only to buy a necktie more quickly and conveniently but also to be informed about a present you hadn't even thought of that would be preferred by the recipient.

As far as financial payback goes, the main issue is that household budgets are relatively fixed and change slowly. Statistics show that median household income, adjusted for inflation, has inched up only slightly over the past 20 years. As with their allotments of free time, people will have to forgo some existing expenditures if they are to spend money on broadband services.

A revolutionary broadband Internet will not happen unless new offerings are markedly different and superior to those available today. In a marketing experiment, Mercer Management Consulting used a virtual-reality interface to present variations of a broadband world to about 1,000 consumers. They were asked whether they would buy various kinds of futuristic services and how much they would pay for them.

Most people said they would be willing to cancel their cable TV subscriptions if the telephone company offered entertainment services or, conversely, to cancel their phone company service if the cable company provided telephone service. They also indicated, however, that they would have to have a good reason for doing so—such as better television reception or a wider range of telephone services.

Although most respondents would reallocate their existing telephone and TV budgets, they said they would spend more money in the aggregate only if the convenience or utility were far greater. For example, they would not spend more money for television service unless there was complete time-shift programming (the ability to, say, order on demand any show aired in the past month) as well as the option of choosing from many thousands of motion pictures and viewing them whenever the subscriber was in the mood.

Open Platforms and Smart Agents

Better access to movies, TV programs, games, gambling and other entertainment does appeal to consumers and could drive the development of broadband. But cheaper, fatter pipes alone cannot deliver on this desire. In the case of broadband television, disparate industry players would have to agree on a standard digital format, find the money to convert to it and then store it in a way that would be economical and accessible to the broadband network. These are expensive and problematic requirements today and will be for some years to come. The thorny issue of intellectual property rights would have to be settled as well.

Offerings must be markedly different and superior.

Succeeding in broadband markets, as we have seen, is not simply a matter of fielding the best access technology. Besides a good and broadly defined infrastructure, the winner will need to predict how customers will derive social utility and value and to build the right business model to deliver the appropriate services profitably.

It will not be easy for providers to determine exactly what subscribers will find valuable. Already customer priorities have undergone dramatic shifts each time connectivity has improved. In the first phase of heavy Internet competition, users contented themselves for the most part with finding a reliable Internet service provider. After the exponential growth of on-line information and Web sites, consumers and investors turned to portals to help them navigate the data

ON-LINE EXPENDITURES of broadband users are more than double those of people whose access to the Internet is via conventional telephone modem, according to data gathered by Mercer Management Consulting in Washington, D.C.

On-line purchases ($ per person "over the past three months")	$76	$187
Information search for product purchases (number of searches per person "over the past three months")	7	16

SARAH DONELSON

overload. Electronic commerce—the buying and selling of goods and services over the Internet—then emerged as the third profit zone.

Although the demand for broadband bandwidth will be strong in the next phase, it will not be sufficient to generate positive economic returns unless compelling applications that greatly improve social utility are also provided. Profit will flow to companies that are able to create products and services that deliver more value than the limited offerings of movies-on-demand and videoconferencing. Indeed, the most savvy service providers, such as telephone and cable companies, will support the development of broadband as an open-standards, fertile software platform from which thousands of novel applications will bloom.

The paradigm will be similar to the one that years ago led to the success of the DOS computer operating system; it came to dominate the software world because Microsoft developed it as an open platform on which hundreds of software companies could create applications. Already an analogous set of network applications, called Web hosting, is emerging.

Today Internet service providers link computers, telephone switches and cable TV installations. But as the Web-hosted world expands, so, too, will the influence of an emerging group of players—the application service providers (ASPs)—which offer Web-hosted applications. These now include such services as managing disparate company databases and running and maintaining servers to provide e-mail to small companies that choose not to buy and install the necessary equipment.

In addition, perhaps five years from now, open platforms will also become one of the key ingredients of a "smart" network. Long-touted smart agent programs—able to rove the network and to do useful work while their users sleep—should

Broadband promises to change people's lives radically.

flourish once broadband searches and analyses are possible. This vision is not far-fetched; already Cisco Systems in San Jose, Calif., and other infrastructure vendors are laying the bricks for the software platform foundation required.

Applications that provide smart agency by raising the personal and professional productivity of users will unlock tremendous value. These are the kinds of services that people will pay more for in comparison with conventional phone or TV services, and when they do, they will help extend broadband penetration.

For both Web-hosted applications and smart agency, the early offerings will most likely be substitutes for current activities. Thus, videoconferencing might replace certain physical meetings, saving travel time and expenses. Virtual game rooms might extend bridge clubs and firing ranges. On-line distribution of music might replace audio compact discs, and video distribution might even replace conventional television. Beyond substitution, however, it is anyone's guess what future applications might emerge; smart agency will create altogether new services beyond our current frame of reference.

Significant Social Shifts

As such innovative services unfold, broadband promises to change people's lives radically. Throughout history, technological advances that seemed small at the time have provoked sweeping, unexpected changes in economic and social structures. When electric power came to U.S. cities in the mid-1880s, it was a luxury item purchased only by the elite. Four generations later electric air conditioning began to spread to ordinary homes and businesses. It was electricity's conquest of the South's climate, coupled with lower costs of living, that made the relocation of factories, workers, managers and retirees from the North desirable.

Thomas Edison and his contemporaries could hardly have foreseen their role in helping the South rise again, and only fools would try to detail the kinds of social change broadband could bring. But we can speculate that the creation of a broadband network made intelligent through smart agency will provoke significant social shifts.

When a broadband application platform finally does emerge, what users can do when connected—and what can be done to them—will be limited only by the imagination of entrepreneurs. They already envision new forms of gambling, "remote" education and medical care, delivery of customized video news to a screen in the kitchen wall, on-line entertainment calendars linked to reviewers' comments and ticket-ordering menus, three-dimensional virtual tours through distant attractions, and automated marketplaces where smart agents will buy and sell for you. Much more, of course, is possible and even inevitable.

As such offerings spill out, some of their effects may not be welcomed, at least initially. For example, vastly greater choice for users could come at the price of an individual's every on-line move being tracked by the network—the classic Big Brother dilemma of technology. Then, too, expanded electronic commerce and electronic entertainment could diminish live contact with people. Broadband users might become more efficient at consumption but at the cost of being attached to the broadband pipe like infants to a bottle and more detached from physical society with its rich serendipity.

In the end, broadband may prove to be a leveler, providing equal access to data and opportunity regardless of wealth. But it could just as likely widen the divide between rich and poor, because information technology to date has generally increased the demand for skilled, higher-paid workers while reducing the need for unskilled workers. Back in the first two decades of this century, rising use of electricity went hand in hand with the employment of more workers with a higher level of education. Yet despite the apparently negative consequences for low-skilled workers, few people today would forgo electric power.

Let us hope that a generation from now we will view the Internet as a blessing that provides every person with a trusted cyber-lieutenant and not as an Orwellian company store to which everyone is bound.

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GEORGE T. HAWLEY worked on transmission system planning for Bell Telephone Laboratories from 1963 to 1983, during which time he received a Ph.D. in electrical engineering from the Polytechnic Institute of Brooklyn. In 1995 he co-founded Diamond Lane Communications Corporation, which was acquired this past March by Nokia, where Hawley is now chief technology officer for the High Speed Access Business Unit. He can be reached at george.hawley@nokia.com.

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JOHN SKORO is the marketing director for the Broadband Wireless Access division of Nortel Networks in Dallas. At Broadband Networks, Inc., which Nortel acquired in 1998, Skoro worked on market strategy for an LMDS system. Previously, during an eight-year tenure at Motorola, he helped to launch the world's first wireless digital two-way communications system.

P. WILLIAM BANE and STEPHEN P. BRADLEY (bill.bane@mercermc.com and sbradley@hbs.edu) write together occasionally on the future of the Internet. Bane is a vice president of Mercer Management Consulting in Washington, D.C. Bradley is the William Ziegler Professor of Business Administration at Harvard Business School, where he is also the faculty chairman of the Executive Program in Competition and Strategy.

Further Reading

RESIDENTIAL BROADBAND. George Abe. Macmillan Technical Publishing, Cisco Systems, 1997.

THE CONVERGING WORLDS OF TELECOMMUNICATIONS, COMPUTING AND ENTERTAINMENT. P. William Bane, Stephen P. Bradley and David J. Collis in *Sense & Respond: Capturing Value in the Network Era*. Edited by Stephen P. Bradley and Richard L. Nolan. Harvard Business School Press, 1998.

RESIDENTIAL BROADBAND: AN INSIDER'S GUIDE TO THE BATTLE FOR THE LAST MILE. Kimberly Maxwell. John Wiley & Sons, 1998.

IMPLICATIONS OF LOCAL LOOP TECHNOLOGY FOR FUTURE INDUSTRY STRUCTURE. David D. Clark in *Competition, Regulation, and Convergence: Selected Papers from the 1998 Telecommunications Policy Research Conference*. Lawrence Erlbaum, 1999.

Excellent definitions and explanations of the many technical terms of broadband and other forms of data communications can be found at www.whatis.com/thespeed.htm on the World Wide Web.

by Ian Stewart

Cone with a Twist

The cone is probably most familiar today as an edible container for ice cream, but its past glories lie in higher realms altogether. The geometry of the cone was known to the ancient Greeks, mainly because of the elegant curves that could be constructed by slicing a cone with a plane. The Greeks delighted in the intricate geometry of these conic sections—the ellipse, parabola and hyperbola—and discovered how to use them to solve problems that were beyond the reach of rulers and compasses.

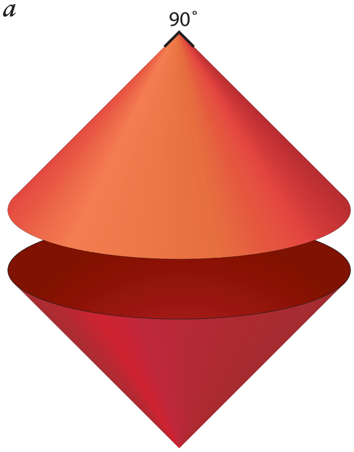
Those problems included trisecting an angle and constructing a cube with twice the volume of a given cube. Both reduce to solving an equation of the third degree—that is, one in which the highest exponent of the variable is three. Conic sections can be used to solve the problems because the points where two sections meet correspond to solutions of equations of the third and fourth degrees. In contrast, rulers and compasses can solve only second-degree equations.

The cone itself has generally been of less interest to mathematicians than its planar sections, perhaps because the cone is so simple in form. Is there anything new to say about this humble solid? Indeed there is. In May 1999 C. J. Roberts, a reader of this column who lives in the English town of Baldock, wrote to me about a very curious shape that he calls a sphericon. He even enclosed two of them in his letter.

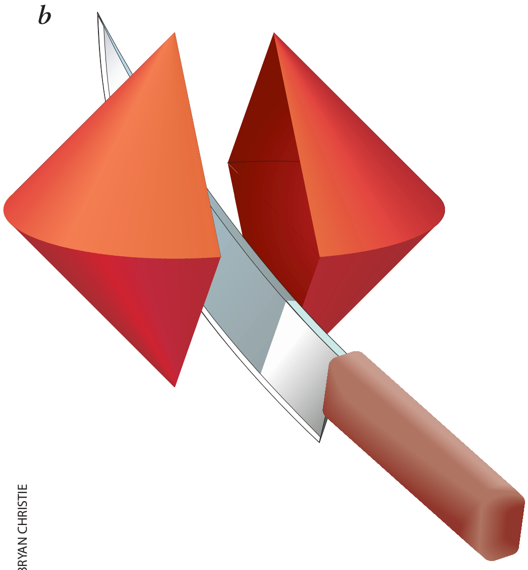
The sphericon [*see illustration below*] is a double-cone—two identical cones joined base to base—but with a twist. It is easy to make. If you slice a double-cone along a plane that includes both vertices, you get a rhombic cross section, a parallelogram with four equal sides. If you use cones of just the right shape, you get a square cross section. Unlike all other rhombuses, the square has an extra symmetry: rotate it through a right angle and it fits back into the same shape. So you can slice such a double-cone down the middle, rotate one of the halves through a right angle and glue the two pieces back together. This is the sphericon. Thanks to the twist, it is not a double-cone but a much more interesting beast. I'd never seen such a shape mentioned anywhere before, but if I'm wrong about its novelty I'm sure that a better-informed reader will quickly tell me.

The sphericon can be made from a single piece of thin card, cut to a shape made from four identical sectors of a circle joined together so that they face in alternate directions [*see illustration on opposite page*]. The main calculation involved in designing this shape is to find the angle between the two straight edges of the sector. Suppose the length of each edge is 1. If the double-cone has a square cross section, the Pythagorean theorem says the base of each component cone has a diameter of $\sqrt{2}$. So the circumference of the base is $\pi\sqrt{2}$. The length of the sector's arc is half that (because you cut the double-cone in half to make a sphericon). The angle of the sector therefore works out to be $\pi\sqrt{2}/2$ radians, or $90\sqrt{2}$ degrees, which is approximately 127.28 degrees.

a

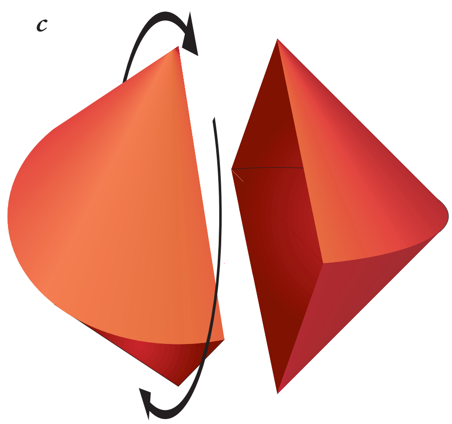


b



TO CONSTRUCT A SPHERICON,
***join two cones at the base* (a), *then cut along the plane that includes the vertices* (b). *Rotate one half 90 degrees* (c), *then glue the halves together* (d).**

c



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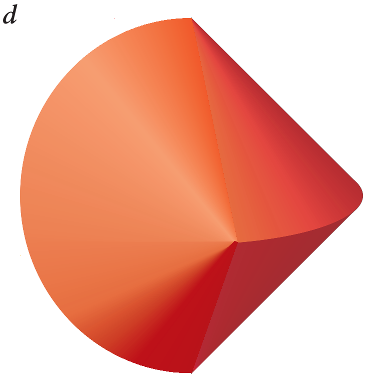
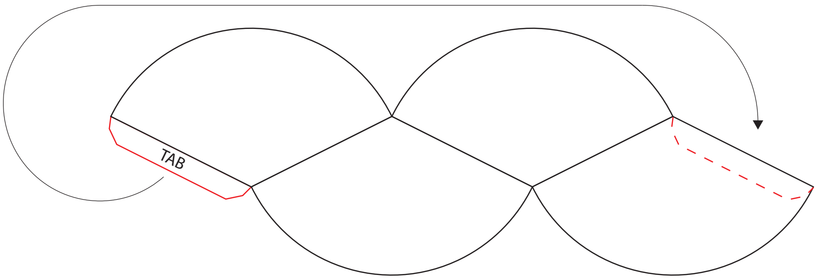


BRYAN CHRISTIE



BRYAN CHRISTIE

AN EASIER WAY TO BUILD A SPHERICON *is to cut a piece of cardboard in the shape above (but enlarged), glue the tab to the matching edge and join the bases of the half-cones.*

If you cut out the shape shown in the illustration, you can roll up the sectors into half-cones and glue the tab to the matching edge. With a little adjustment the bases of the half-cones will fit snugly with no gap, and you can tape the joins.

The first delight of the sphericon is: it rolls! A cone placed on a flat surface rolls around in circles. A double-cone can roll in a clockwise circle or a counterclockwise one, but it rolls straight only if you rapidly bowl it or set it on rails. A sphericon performs a controlled wiggle, which on average is straight. First one conical sector is in contact with the flat surface, then the next. So as it moves forward it wiggles alternately to the left and right. It is especially interesting to start it at the top of a gradual slope and watch it wobble its way down. After reading the letter from Roberts, I spent a pleasant half-hour with several other mathematicians rolling sphericons along a table.

The letter also hinted at some of the sphericon's fascinating attributes: it has one continuous face, and one sphericon can roll around another ad infinitum. Intrigued, I asked for more information, and in return Roberts sent an enormous cardboard box that weighed virtually nothing. It contained a large lattice of about 50 sphericons, neatly assembled with transparent tape. This lattice, like the atomic lattice of a crystal, repeats indefinitely in three dimensions.

One reason why the sphericon has such neat geometric properties is that its four "edges"—the lines where the component sectors meet—lie along four of the edges of a regular octahedron. The other four edges of the octahedron correspond to lines that bisect the vertex angles of the sectors. The octahedron, in turn, is closely related to the cube: if you put a dot in the middle of each face of a cube and join the dots by straight lines, you get an octahedron. And cubes, of course, stack in a regular manner to form a flat layer or fill three-dimensional space.

Roberts, who is 47, invented the sphericon about 30 years ago. Geometry was his strong point at school, and he started work as a joiner's apprentice. Not surprisingly, therefore, his first sphericon was carved out of wood. His starting point was the well-known Möbius strip, a band of paper joined end to end with a 180-degree twist. Roberts realized that because paper has a definite thickness, the band's cross section is really a long, thin rectangle. If you make the cross section into a square, you can join the ends with a 90-degree twist instead, producing a solid whose outer surface consists of a single curved face. This shape, however, has a hole in the middle: it is a ring. Does there exist a solid that is not a ring whose outside has a single curved face? One day, while Roberts was working on a length of wood with a square cross section, he started thinking about blending one face into the next by planing a curve around the ends. Do this at both ends, eliminate the wood in between, and you get a sphericon.

He made one out of mahogany and gave it to his sister, who has kept it ever since. Then he forgot the topic until 1997, when I gave a series of televised mathematics lectures and talked about symmetry. At that point Roberts's interest was revived, and he wrote to me.

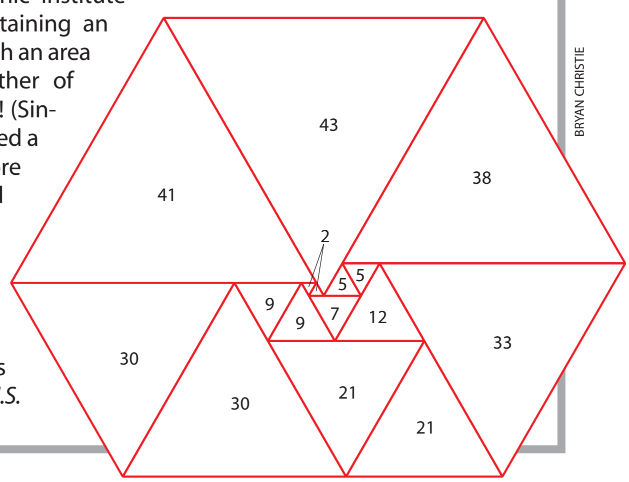
If two sphericons are placed next to each other, they can roll on each other's surfaces. Four sphericons arranged in a square block can all roll around one another simultaneously. And eight sphericons can fit on the surface of one sphericon so that any one of the outer solids can roll on the surface of the central one.

The possible arrangements of sphericons seem endless. I leave to readers the pleasure of playing with this extremely clever mathematical toy and inventing new patterns for themselves. SA

FEEDBACK

The Feedback section that accompanied "Squaring the Square" [July 1997] began a correspondence that is still ongoing. Robert T. Wainwright of New Rochelle, N.Y., asked: What is the largest convex area that can be tiled with equilateral triangles whose sides are of integer length (with no overall common divisor)? Later Feedbacks reported some of your results: in particular, arrangements of 15 tiles with areas of 4,751 [August 1998] and 4,782 [March 1999]. (For convenience the area is measured in units equal to the area of the smallest triangle.)

I inadvertently overlooked a letter sent to me in March 1998 from John W. Layman of Virginia Polytechnic Institute and State University containing an arrangement of 15 tiles with an area of 5,114—larger than either of those that I later reported! (Sincere apologies. I clearly need a better filing system.) More recently Layman has found an arrangement of 16 tiles with an area of 9,158 (*right*) and one of 17 tiles with an area of 16,655. He has also found an arrangement of 18 tiles with an area of 29,214. *—I.S.*



BRYAN CHRISTIE

by Shawn Carlson

Modeling the Atomic Universe

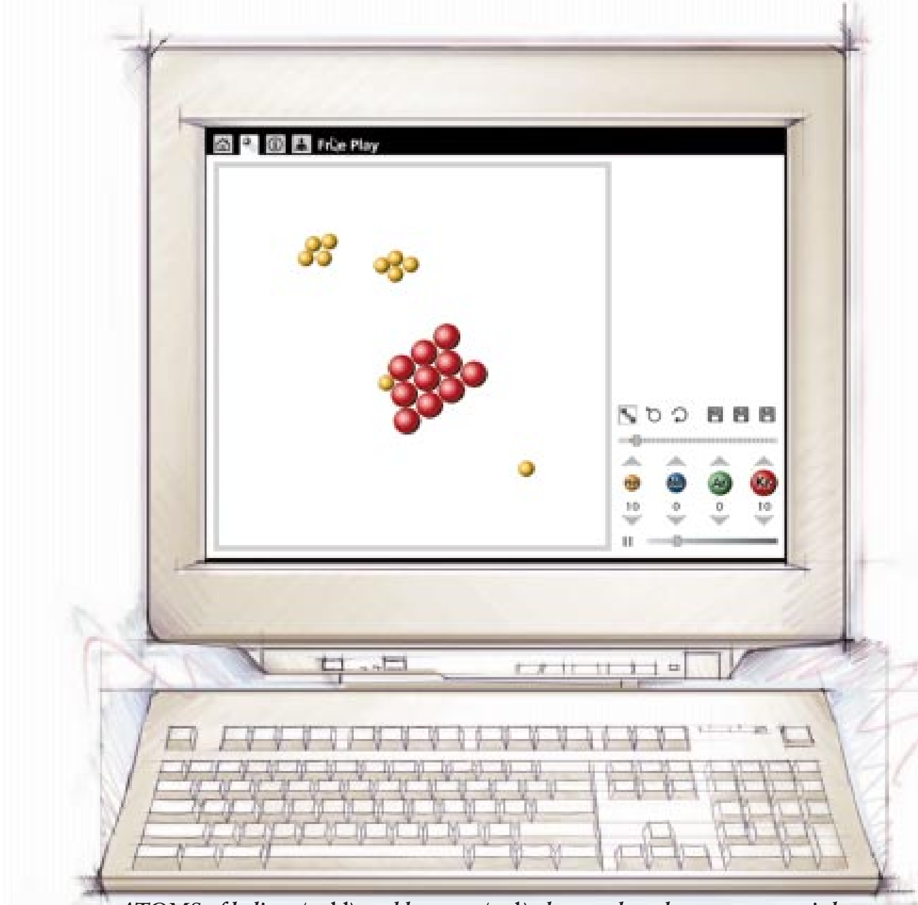
Grant that the universe is filled with atomic-size billiard balls. Then, with a few insightful definitions and some mathematical gymnastics, physicists can provide you with a near-perfect explanation of our everyday world. The theory is called statistical mechanics. Many people know that it limits the amount of work a machine can deliver. But it actually goes much further. Statistical mechanics describes the engines that drive the earth's weather. It governs the temperatures and pressures inside stars and constrains the evolution of the cosmos. It even sheds light on the arrow of time—why we remember the past and not the future. Indeed, Albert Einstein and Richard Feynman saw the theory as the highest achievement of classical physics.

Sadly, many amateurs have avoided this important subject because, in this case, the highest plateau is also the hardest to reach. One cubic centimeter of air at atmospheric pressure contains more than 10 billion billion atoms of various sizes, all smashing into one another at different speeds. No computer can project the exact trajectories of all these particles, and even if one could, no human mind could make sense of it. Therefore, physicists have devised clever but devilishly difficult mathematical methods to extract comprehension from the chaos.

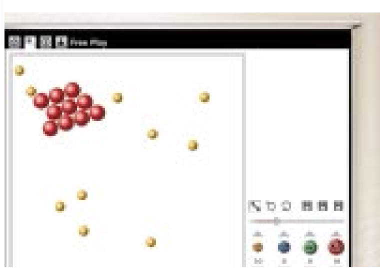
But the subject is not as abstruse as it seems. The trick is to find models that let you visualize how these random collisions average out to yield the familiar properties of matter, such as temperature, pressure and entropy. The right mental pictures can elucidate the behavior of materials and in turn can help advance amateur projects involving chemistry, sound, heat transfer, crystals and vacuum techniques. That's why I'm pleased to let you know about Molecular Dynamics, an innovative piece of educational software. It doesn't cover every topic within classical statistical mechanics, and it ignores quantum-mechanical effects completely. But it is still the most accessible modeling software I've seen. What is more, the authors of the program at Stark Design in Morristown, N.J., have made it available to *Scientific American* readers for free until October 2000.

This kind of simulation is nothing new. Many amateur scientists fondly remember writing such programs back in the days of hobbyist computing [see Computer Recreations, by A. K. Dewdney; SCIENTIFIC AMERICAN, March 1988], and several limited versions are available on the World Wide Web (such as a Maxwell's demon game at cougar.slvhs.slv.k12.ca.us/~pboomer/physicslectures/maxwell.html).

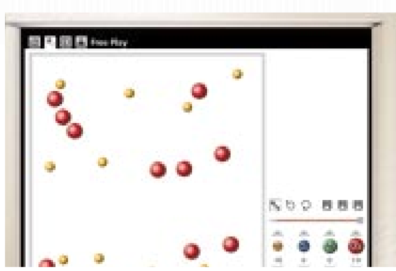
But Molecular Dynamics takes this all to a new level. It allows you to conduct an impressive array of virtual experi-



ATOMS of helium (gold) *and krypton* (red) *clump when the temperature is low ...*



but as the gas heats up, the lighter heliums are torn asunder ...

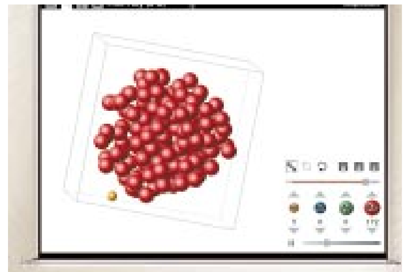


and at still higher temperatures, the heavier kryptons fly apart, too.

GEORGE MUSSER; DANIELS & DANIELS; SOURCE: MOLECULAR DYNAMICS

3-D VIEW shows a cool crystal of krypton with a few helium atoms on its surface.

At higher temperatures, the heliums meander about the surface …



and at still higher temperatures, the whole thing disintegrates.

GEORGE MUSSER; DANIELS & DANIELS; SOURCE: MOLECULAR DYNAMICS

ments to see how different atoms interact under all kinds of conditions. The program consists of numerous modules that demonstrate diffusion, osmotic pressure, the relation between temperature and pressure, the distribution of molecular speeds in a gas and many other topics. And you can use the software to discover things that even the most mathematically gifted physicist would be hard-pressed to wrestle from the basic theory.

The simulation runs so fast that when I first saw it at a conference I was certain it was a trick. The presenter put about 50 each of four different kinds of electrically neutral atoms inside a three-dimensional volume. The particle positions updated so quickly that I thought it had to be a computer movie, not a real-time simulation. So I decided to challenge the fellow.

In nature even neutral atoms can bond together. The mutual repulsion of the orbital electrons polarizes the atoms, and it turns out there is a range of distances over which these polarized atoms are attracted. So I asked the presenter to add these electrostatic interactions and then slowly decrease the temperature. He did. The heavier atoms began clumping together while the lighter ones kept speeding about, just as they should. He then rapidly brought the temperature to zero. The free atoms settled into small isolated clumps, again just as they should. That made me a believer.

Geologists see this clumping effect because a volcanic rock that cools slowly possesses larger mineral grains than one that cools quickly. Molecular Dynamics makes it possible to study the underlying principles of this process (called annealing) by varying the number and kind of atoms as well as the rate of cooling. By pausing the simulation at each temperature and rotating the virtual container, one can count the clumps and see how many atoms of which type are in each. That suggests an interesting study. Try repeating the experiment a few times and plotting the average size of the clumps versus the cooling rate. You may discover some fundamental facts about annealing that are quite difficult to derive mathematically.

One delightful demo starts with a cubic crystal of 63 krypton atoms. A few added helium atoms quickly bond to the surface. Tweaking the temperature upward causes the helium atoms to walk randomly on the crystal's face. At a little higher temperature the heliums leave the crystal, and if you raise the temperature still further, the crystal will fly apart. These kinds of effects are observed in real crystals. You can do other experiments here as well. Try lowering the temperature and see whether you can get the crystal to re-form. Then plot the time required for the krypton crystal to form versus the number of hydrogen atoms bouncing about. Does the hydrogen interfere with the crystal formation and, if so, why?

You can also explore gas behavior, such as how a gas adjusts to changes in temperature, volume, or number and types of its atoms. The simulation can approximately reproduce the proportionalities that are combined into the well-known ideal gas law. But only approximately. That is because the ideal gas law itself is just an approximation. It holds only if the gas atoms occupy a negligible fraction of the container's volume and if the atoms' kinetic energies are much larger than the interatomic potential energies that tend to make them clump together. As a result, any real gas departs from the ideal gas law at high densities or low temperatures. Molecular Dynamics includes these effects automatically.

My favorite module, "Maxwell-Boltzmann Speed Distribution," lets you discover how few atoms you need before the physicists' mathematical tricks start working. One of the early triumphs of statistical mechanics in the 19th century was its ability to predict the fraction of atoms moving with a particular range of speeds within a gas at a given temperature. The curve of the fraction versus speed has a sharp rise—meaning there are fewer atoms at lower speeds—and a long tail, indicating that some atoms have speeds that are much higher than the average. I placed 100 atoms of helium and argon into the box and watched the distribution of speeds in real time. After just a few collisions, the two curves took on the expected shape. The heavier atoms peaked at a slower speed, as the theory predicts. You might enjoy removing atoms and observing how the distributions deteriorate.

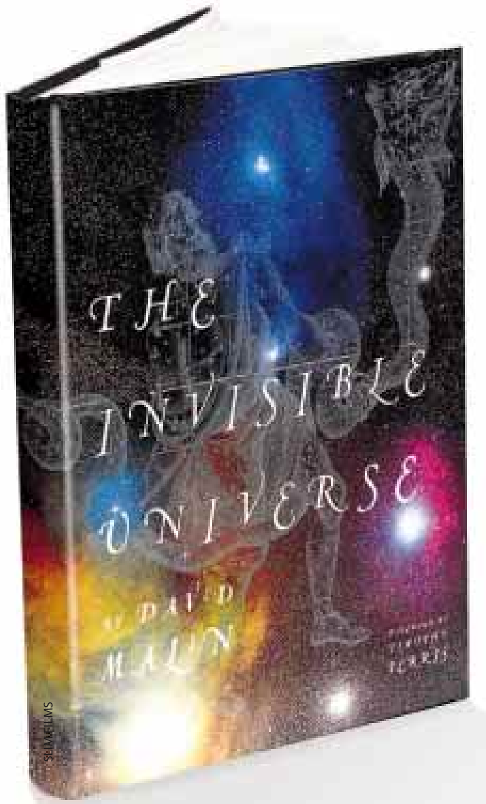
Unfortunately, the software does have some glaring omissions. For instance, it does not allow treatment of heat flow, work or entropy. You cannot, for example, simulate a piston. Also, the support materials were clearly developed by educators with different views of the target audience; some sections are aimed at beginners, whereas others are perhaps more appropriate for graduate students. The software designer has set up a special Web page for *Scientific American* readers to submit suggestions for a future version. Despite its limitations, Molecular Dynamics is a wonderful aid for understanding how atoms build up our universe. And for free, how can you possibly go wrong?

To download your free copy of Molecular Dynamics, link to Stark Design's site at www.starkdesign.com/sciam on the World Wide Web. For more information about this and other projects, check out the Society for Amateur Scientists's Web site at earth.thesphere.com/SAS. You may write to the society at 4735 Clairemont Square, PMB 179, San Diego, CA 92117, or call 619-239-8807.

PHOTOGRAPHER TO THE STARS

Review by Leif J. Robinson

The Invisible Universe
BY DAVID MALIN
Bulfinch Press/Callaway, New York, 1999 ($50)



SLIM FILMS

Images, images, images—how easily the bounty of astronomy seduces us! What other science can showcase portraits as profound as the birth of the universe or the death of a star?

It's all Galileo's fault. In 1610, through the newly invented telescope, tiny as it was, he began to sketch a realm beyond the ken of anyone who had looked before. The moon, he discovered, had mountains and plains; Venus cycled through phases; Jupiter sported four satellites; new stars were everywhere. Ancient ideas about our world's place in the universe started to crumble: science, religion and philosophy have never since been the same.

David Malin, it is fair to say, invented *spectacular* astronomical imaging—the kind that catches the eye of even the most disinterested modern passerby. He accomplishes it "the old-fashioned way," through laborious hours in a smelly darkroom. There he fuses multiple images of star-filled galaxies and glowing gaseous nebulae into colorful and scientifically valid artwork, much as a painter layers watercolors to create the perfect tone and ambience. He suppresses film's artificial harshness to reveal delicate celestial texture. In short, like Galileo, he unveils a hitherto unknown universe.

Malin's legacy of innovative astrophotography is now a quarter-century old. He brings this corpus of work together in *The Invisible Universe,* a portfolio of 50 celestial portraits taken with the 3.9- and 1.2-meter telescopes at the Anglo-Australian Observatory in New South Wales, Australia. Many of his pictures might be seen by astronomical aficionados as warhorses. They are not. At this book's oversize scale (13 3/8 by 16 inches) and with state-of-the-art reproductions overseen by the author, starscapes effervesce with new vibrancy. Furthermore, a few novel scenes accompany the familiar ones.

So what does *The Invisible Universe* contain? Images of nebulae make up about 60 percent of the presentations. Galaxies account for about 20 percent, and the rest embrace star clusters, star fields and the detritus from exploded stars. Malin's subjects are strongly biased toward those located south of the celestial equator; that is an asset, because the Northern Hemisphere sky has long been overworked.

The format is elegant. Each of Malin's full-page pictures faces a page that contains two or three paragraphs of explanatory text, a small image from a historical work—mainly sketches by John Herschel or selections from a classic star atlas—and a thought-provoking poetry excerpt. Indeed, this book's greatness stems from the amalgam of all these parts.

Like many artists, the author is multidimensional, evocative with words as well as images. He writes: "We see a nebula with the delicate construction of an open rose, the bright stars at its center glistening like ripe stamens. Just like the petals of a rose or an ornate wreath, the nebula encloses an almost empty space, a hollow interior excavated by the energetic young stars inside. There is nothing as substantial as a flower here; nor is the Rosette Nebula a gentle place of quiet beauty." Describing another of his beloved nebulae: "The alignment of countless dusty grains gives the light reflected from the trio of bright stars a silky appearance, glinting in the starlight—like locks of newly brushed hair." Good stuff!

Malin's introduction to his gallery is substantial and will satisfy all but the most fussy reader. Star lore and history are nicely balanced against a synopsis of what we know about the physical makeup of the universe and the entities it harbors. "It is not the immensity," he writes, "or even the beauty, of the universe that is so humbling; rather it is that we know so little about it."

The text accompanying the pictures disappointed me a bit. It is sometimes repetitious (yet how many elegant variations are available to describe the way a nebula works?). And it is historically narrow, lionizing the 18th-century celestial ferret Charles Messier and his Southern Hemisphere clone, John Herschel. (Many other gifted observers in the prephotographic era contributed mightily to our early awareness of the deep sky.) The text is also occasionally glib, so that only the cognoscente will easily hop from one thought to the next without falling off the page. Perhaps the restriction of format was an undoing here.

One of the appendixes contains an almost afterthought overview of the photographic techniques Malin employs to create his portraits (he combines separate exposures in red, green and blue light). He should have gone much further with this description. Many of his pioneering techniques, once employed only by himself and a handful of other experts in the best-equipped darkrooms, are now emulated nightly by thousands of amateur astronomers who boot up digital image-processing programs.


FROM THE INVISIBLE UNIVERSE

Rosette Nebula

Another appendix includes a list of the 50 brightest stars, which seems gratuitous. And a third features Messier's well-worn catalogue, although here it is augmented by a very provocative "southern extension" of deep-sky objects that "Messier would probably have identified had he lived at the latitude of Sydney or Cape Town or Santiago."

I am sorry that the dates of Malin's exposures were not included, for they would have shown that years often passed between the first and last images needed for a set of three. To add a crucial exposure, he often had to wait for scraps of observing time when "real science" wasn't ongoing.

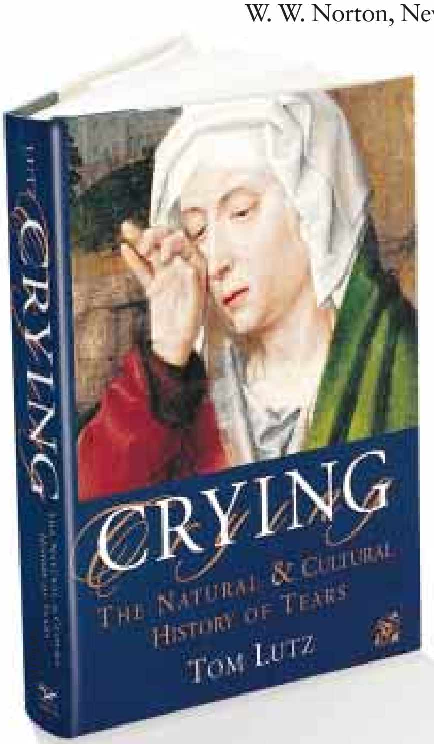
Great art prevails, and Malin's portraits—in words as well as in pictures—should inspire generations. For his many fans, this work is a must-get. And someone wishing only to cover a coffee-table blemish could spend much more for much less.

LEIF J. ROBINSON is editor in chief of Sky and Telescope *magazine.*

WEEPING WITH THOSE WHO WEEP

Review by Claire Panosian

Crying: The Natural and Cultural History of Tears
BY TOM LUTZ
W. W. Norton, New York, 1999 ($25.95)



Last May I visited a dusty, makeshift clinic housed in a warehouse on the outskirts of Tirana, Albania. As a volunteer doctor from the U.S., I was helping to deliver primary health care to Kosovar refugees who had fled their homeland just six weeks earlier. Viewing the queue of waiting patients, I beheld a sea of minor ailments accented by a few flat stares of classic post-traumatic stress disorder. What memories lay behind those stares, I wondered—masked thugs, burnt villages, a head held at gunpoint? Because there was no way to know, I focused on the work at hand. Essentially routine stuff: sore throats, diarrhea, crusty skin rashes.

Then, in the midst of peering at tonsils and tendering antibiotics and unguents, I met a young father. Quietly, through a translator, he told this story. In March, Serb soldiers knocked at his door. They pointed guns and demanded money. Encountering resistance, they proceeded to terrorize his wife by dropping their three-year-old daughter out a second-story window, then down a well. Miraculously, the girl escaped drowning by clinging to a ledge. Hours later our patient rescued her, shivering and scratched but otherwise okay. The family left that night.

So what was his reason for seeking medical advice now, I inquired, half holding my breath from the horrifying exodus account. His little girl would not stop crying, he replied. In fact, for six weeks she had cried—no, wailed—nearly every waking hour. She cried instead of eating. She cried instead of playing. And at the end of the day, at last drained of that day's grief, she cried if anyone other than he laid her down to rest.

Crying has been called a universal human language, especially in the young. According to animal researchers, it is also an exclusively human means of expression. Yet despite our rich knowledge of neurophysiology and psychology, we in medical science still cannot predict the whens, wheres and whys of crying that vary from person to person and culture to culture. If that despairing Kosovar child had been born into the Tiv people of northern Nigeria, for example, she might not have cried at all. In the Tiv culture, parents and caretakers discourage crying from infancy by laughing at babies, cupping their mouths, pinching their nostrils, and even on occasion by nipping and slapping them at the first sign of a tearburst.

The latest homeopathic remedy for grief is a dilute solution of one's own tears.

Tom Lutz, author of *Crying: The Natural and Cultural History of Tears,* covers the Tiv tradition as well as other interpreters of crying from Sigmund Freud to Jean-Paul Sartre in a lushly researched book that surveys, in the writer's own words, "the arts' and sciences' understanding of tears." This book's goal, to state the obvious, is daunting. But Lutz, an academic humanist who has also written on American nervous disorders at the turn of the century, is impassioned. How else could he have mined the respective literature on tears by physiologists and historians, psychologists and storytellers, sociologists and anthropologists?

In doing so, Lutz rediscovers historical prejudices that to this day affect research into human emotion. Take, for example, Descartes's position that emotions are simple bodily reactions, separate from the workings of the mind, or Plato's characterization of passion and reason, in Lutz's paraphrase, "as two mismatched horses pulling the chariot of the soul." In another chapter, Lutz traces Freud's discrediting of crying as catharsis while cultivating ideas that would convince behaviorists to see children's tears as not only expressive but manipulative.

Of course, there is a downside to sampling so broadly from diverse academic traditions outside one's own. Lacking the authority of an expert, the author becomes part reporter, part translator, part voyeur. At times I suffered an awkward mind-bend traversing one chapter to the next—each steeped in the language and theory of its favorite research disciples—and longed for Lutz the cataloguer to put forth his own thesis.

In the final third of his book, Lutz is on more familiar turf. Here he examines the "uses" of crying—for example, in politics and romance—and the history of literary and artistic tears. Tapping sources from ancient Greek texts to contemporary newspapers, Lutz describes how tears and tearlessness have wreaked revenge, seduction, escape and empathy. A 1996 *New York Times* story quotes a Hutu mother who says, "It is useless to cry," and who plans to systematically replace her five massacred children, thus avenging the atrocities inflicted on her. In contrast, Lutz views Oliver North's talent for "getting moist" at key moments during his Contragate testimony as a masterly example of tears commanding public empathy, in this case for a misunderstood hero.

Scanning the recent electoral landscape, Lutz also postulates a sea change in the political currency of tears. In 1972 Edmund Muskie was counted out of the presidential race after crying in front of reporters, as was Pat Schroeder in 1988. But in the 1990s Bob Dole—a dry-eyed politician for 40 years of public life—cried at President Richard Nixon's funeral. Several years later during his own presidential campaign, Dole welled up repeatedly when reliving his wartime experiences. Although tears didn't win him the election, Dole, now transformed from Midwestern stoic, symbolizes a male torchbearer for a new era in American politics.

The last chapter is entitled "The End of Tears." Biblical parables, Homeric verse, native customs—all are studied for lessons on how we stop crying. One conclusion, supported by common wisdom as well as research, is that ceasing to cry, in Lutz's words, "is often a matter of learning how to feel something else." In this chapter we are also warned by modern thinkers such as Daniel Goleman (author of *Emotional Intelligence: Why It Can Matter More Than IQ*, 1995) and Steven Pinker (author of *How the Mind Works*, 1997) against the dangers of emotional flooding—a shift from a recycled generation of crying-as-catharsis advocates of the 1970s. There's even a little something for New Age devotees. The latest homeopathic remedy for grief, it appears, is drinking a dilute solution of one's own tears.

In sum, *Crying: The Natural and Cultural History of Tears* is something like Alice's journey through the looking glass—a kaleidoscopic feast, in this case, of creative thought and outpourings of the soul on the subject of human emotion. But, like Alice, I hungered for a wise counselor, a guide who knew the journey's end. Perhaps Lutz's decision to abstain from this role is his own commentary on the mystery of a response so profound and ineffable as human tears.

Of course, none of this helps the little girl from Kosovo. Weeks after I left Albania, I heard she was still weeping.

CLAIRE PANOSIAN is professor of medicine at the University of California at Los Angeles School of Medicine and a medical journalist. Her articles and essays have appeared in Discover, *the* Los Angeles Times *and the* Chicago Tribune.

THE EDITORS RECOMMEND

STRANGER IN THE NEST: DO PARENTS REALLY SHAPE THEIR CHILD'S PERSONALITY, INTELLIGENCE, OR CHARACTER? David B. Cohen. John Wiley & Sons, New York, 1999 ($27.95).

Parents, perhaps you can relax a bit. According to Cohen, professor of psychology at the University of Texas at Austin, there is only so much you can do in raising your children, and even that may not have the results you hope for. "Most basically," he says, "when it comes to individual development, the influence of heredity and prenatal life (nature) is surprisingly strong, the influence of rearing and family life (nurture) is surprisingly weak, and the somewhat chancy interactive effects of nature and nurture are surprisingly perverse." Thus it is, he declares, that most abused children do not become abusive parents, whereas some well-loved children grow up to be monsters. And thus it is that adopted children show more of the traits of their biological parents than of their adoptive parents and that identical twins reared apart show almost identical traits. The powerful effect of heredity on a developing child is what so often causes "unexpected behaviors that contradict parental expectations or that embarrass scientific theories" and make a child seem like a stranger in the nest. Nevertheless, parents should not give up entirely. They can hope to maximize their influence by "old-fashioned disciplined rearing."


FROM STRANGER IN THE NEST

WIND: HOW THE FLOW OF AIR HAS SHAPED LIFE, MYTH, AND THE LAND. Jan DeBlieu. Houghton Mifflin Company, Boston, 1999 ($14).

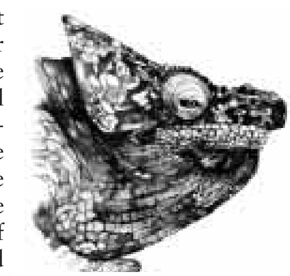
DeBlieu, who writes for a living, has a poetic touch that adds a special grace to her prose when she turns to a subject in nature. The prose and the venturesome research behind it won the 1998 hardcover version of this book the John Burroughs medal for distinguished natural history writing; this is the paperback edition. "The wind, the wind," DeBlieu writes. "Few other forces have so universally shaped the diverse terrains and waters of the earth or the plants and animals scattered through them. Few other phenomena have exerted such profound influence on the history and psyche of humankind." She explains lucidly the physics of wind and describes her trips to experience the wind—including the time she had herself strapped into a hang glider, towed to 2,000 feet and turned loose.

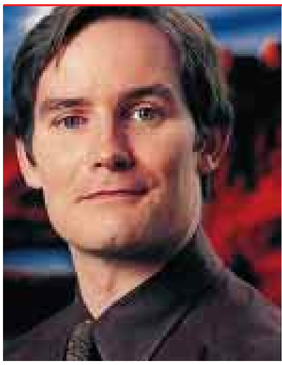
THE ORIGINS OF LIFE: FROM THE BIRTH OF LIFE TO THE ORIGINS OF LANGUAGE. John Maynard Smith and Eörs Szathmáry. Oxford University Press, New York, 1999 ($25).

Maynard Smith and Szathmáry are intrigued by the complexity of organisms. "The more we know about them—their biochemistry, their anatomy, their behaviour—the more astonishing are the detailed adaptations that we discover. How could all this complexity have arisen?" Darwin's theory of evolution by natural selection cannot alone account for it; that theory predicts only that organisms will get better at surviving and reproducing in their current environment, not that they will become more complex. The answer, according to the authors, is that organisms increase in complexity as a result of "a small number of major changes in the way in which information is stored, transmitted, and translated." Maynard Smith (emeritus professor of biology at the University of Sussex) and Szathmáry (at the Institute for Advanced Study in Budapest) call these changes "the major transitions" and cite eight of them in evolutionary history, beginning with replicating molecules and ending—at least for now—with the development of human language. In explaining the transitions to a general readership, the authors provide a clear-eyed review of a large part of modern biology.

ISLANDS: PORTRAITS OF MINIATURE WORLDS. Louise B. Young. W. H. Freeman and Co., New York, 1999 ($23.95).

Young's verbal portraits are handsomely framed by apt quotations from the likes of Shakespeare, Browning and Ovid as chapter headings and by elegant drawings of island fauna and phenomena by Jennifer Dewey. "The remoteness of islands surrounds them with a certain mystery," environmentalist and geophysicist Young says, "and their isolation is responsible for their individual characteristics and evolutionary history." She portrays vividly the characteristics and the evolutionary history of 12 islands or island groups—among them the Hawaiian archipelago, the Galápagos, Easter Island and Madagascar—and also treats Earth itself as "an island in the universe."


FROM ISLANDS



ERICA LANSNER

COMMENTARY

A Total Eclipse of Reason

by John Rennie

This past August took me to Munich for a viewing of the total solar eclipse. Years of casual study about total eclipses could not prepare me for the merciless beauty of our sun as an unfathomable black disk ringed in angry white fire. And the experience reminded me of how thin the veneer of human rationality could be: standing in a field under the weird end-of-the-world light, I felt some of the historical fear of those events, as though monsters might suddenly claw their way out of the earth to carry us away. But then the bright light of reason returned, and I got over it.

Meanwhile, back in the U.S., the Kansas State Board of Education was trying to turn out the lights more permanently. Acting out of a covert social agenda, it decided that teachers could omit mentioning those inconvenient ideas, evolution and the big bang.

This is just an embarrassment. And a betrayal of the majority in Kansas, who I believe know better. At the end of the 20th century, for an allegedly responsible governing body to endorse ignorance of evolution and modern cosmology *as a more appropriate way to teach science* is a grotesque perversion.

The reasoning—I gag at calling it that, but carry on—behind this decision is that evolution and the big bang are just theories, not facts. As such, other explanations for how life and the universe came to be are not only equally valid, they're equally scientific. Never mind that biologists and astrophysicists find overwhelming evidence in support of these ideas. They must be biased.

Why stop at evolution and cosmology, though? Let's make sure that the schoolkids of Kansas get a really first-rate education by loosening up the teaching standards for other so-called scientific ideas that are, after all, just theories. The atomic theory, for example. The theory of relativity. Heck, the Copernican theory—do we really know that the universe doesn't revolve around the earth? It sure looked that way during the eclipse.

The irony is that so many people are worried about the state of science education in this country for the wrong reasons. As W. Wayt Gibbs reports in this issue in "The False Crisis in Science Education," although many policymakers are in a dither about poor science teaching leaving the U.S. uncompetitive, little suggests that American students are doing badly at all. The real crisis is not that science is being taught poorly; it's that meddlers in Kansas and elsewhere are stopping science from being taught, period.

Joking about flat-earthers in Kansas is easy. Ranting about it, easier still. But I'm calling on educators and anyone else who can to act.

If you are on the admissions board of a college or university anywhere in this country, please contact the Kansas State Board of Education or the office of Governor Bill Graves (785-296-3232 or e-mail, governor@ink.org). Make it clear that in light of the newly lowered education standards in Kansas, the qualifications of any students applying from that state in the future will have to be considered very carefully. Send a clear message to the parents in Kansas that this bad decision carries consequences for their children.

If kids in Kansas aren't being taught properly about science, they won't be able to keep up with children taught competently elsewhere. It's called survival of the fittest. Maybe the Board of Education needs to learn about natural selection firsthand.

JOHN RENNIE is editor in chief of Scientific American.

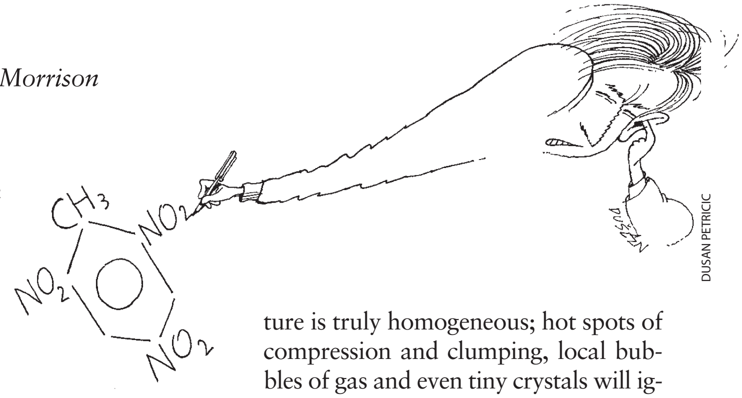
BECKER AND BREDEL *AP Photo*

Kansas turned out the lights more permanently by endorsing ignorance of evolution.

WONDERS

by Philip and Phylis Morrison

Nitrogen: The Dark Side



In our August column we described the bright virtues of nitrogen as a nutrient. After the return of the Star Wars myth, we are drawn to consider nitrogen again, this time its dark side, for most explosives are nitrogenous.

In the beginning came saltpeter, the indispensable nitrogenous ingredient of an experiment first reported in the ninth century by a Taoist alchemist. He warned that a mix of saltpeter, sulfur and a carbonaceous stuff (dried honey?) had burned hands and faces "and even the whole house." From that quixotic hint, the Chinese high technicians developed gunpowder and before 1200 had gone all the way to the devices we know as guns and cannons. The lagging West was not slow to catch on, and in a demonstration of the compelling power of reality, some unsigned peers of the old Taoist ended their own recipe, a little before 1300, with a similar caution, save in Latin: "It is forbidden to make this … under a roof because of the danger."

Saltpeter was long used in old China in metallurgy and drug preparation. It is a white, chalky natural mineral, encrusting the ground widely in many warm but not too humid locations in China and in India. The compound sought is potassium nitrate, highly soluble. Saltpeter collection became a state concern in Europe, where the mineral is not common. There a white crust was scraped off damp walls and floors of barnyards and stables, where it appeared after lengthy exposure to animal and plant manures.

Early chemical technology knew how to purify the right stuff by harvesting its crystals from a solution of the crude saltpeter. Thorough but gingerly grinding of a combo of 75 percent white saltpeter by weight, with 15 percent black charcoal and 10 percent yellow sulfur yields a grainy, gray-black, intimately mixed gunpowder, still in wide use. Gunpowder burns rapidly unconfined, far faster confined by a firecracker paper, let alone the strong grip of a forged gunbarrel. (We ought not to ignore the bright side of gunpowder, for fireworks are still propelled and made fiery for the public delight mainly by the mix, if often less rich in nitrates than gunners favor.)

No unusually high energy release distinguishes an explosive from other combustibles. It is the power, the rate of energy release over time, that rules. Even a high explosive burns with about the same energy release per gram as does firewood. The scale on which fuel and oxidizer are mixed is key. The atoms of a burning splint of wood must somehow come into contact with the oxygen atoms of outside air. In gunpowder the oxygen atoms of the saltpeter lie within, and the delay is only to allow the atoms to cross the distance between minute particles of oxidizer and fuel. But in the newer high explosives, oxygen, nitrogen, hydrogen and carbon atoms dwell together within every single molecule. They are "mixed" at the atomic scale, able to collide at once with one another on vaporization.

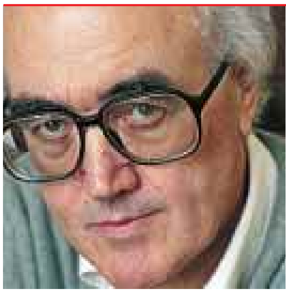
The detonation in Oklahoma City signaled the compound's dual nature—and our own.

The speed at which the reaction propagates down a long explosive sample can be measured. An unconfined train of gunpowder burns speedily, some millimeters per second. Confinement increases pressure, so that the first gaseous products are denser and hotter. No mixture is truly homogeneous; hot spots of compression and clumping, local bubbles of gas and even tiny crystals will ignite and burn first. As local pressure rises, the gases become still denser, more hot spots form, more gas bubbles burn, until at last the whole is afire. Well-confined modern propellants can burn at rates up to a millimeter in a *microsecond;* nowadays they are not powders but grains of homogeneous nitrated organics, extruded by design with shapes and gas spaces. In milliseconds the charge turns into very hot gas compressed a few thousandfold from the original powder volume, although the reaction front advances only at subsonic speed.

The term "high explosive" is retained for compositions, like TNT, whose explosion front spreads at supersonic speed; that detonation, once it is set going, is not much changed by confinement. These reactions are faster by far than those of the best propellants; they speed along at some six to 10 millimeters per microsecond. Most—not all—of the vaporized atoms supply maximum energy by relinking promptly into such stable molecules as N_2, H_2O and carbon dioxide.

Nitration is achieved by linking one or more of the simpler oxides of nitrogen to an organic molecule. That molecule may be a familiar petrochemical product, like the toluene whose molecular ring of carbon and hydrogen is redecorated by symmetrically adding three NO_2 groups to form tri-nitro-toluene, TNT. Superficially resembling an ordinary oil refinery, the intricate piping of a modern chemical plant can be designed with controlled stages, temperatures and pressures fitting the catalysts, to produce nitric acid from ammonia and oxygen, ammonium nitrate from nitric acid and oxygen, or urea, a safe fertil-

Continued on page 127



CONNECTIONS

by James Burke

A Matter of Degree

DUSAN PETRICIC

I was on the flight deck of a transatlantic triple-7 recently, watching the onboard navigational magic, when it occurred to me that it all went back to those two 18th-century French expeditions, sent to see if one degree of the meridian was longer up north than at the equator. The guy they sent south to Peru was the intrepid Charles-Marie de La Condamine, who discovered that the equatorial degree was the shorter (because of the earth's being an oblate sphere). On his way home in 1743, La Condamine rafted down the Amazon, scribbling busily as he floated along. One of the zillion things he described in passing was the *hevea* tree. Whose dried sap made a miracle substance that did something that, to 18th-century eyes, was weird and wonderful. It bounced.

By 1820 an English coach builder name of Thos. Hancock was buying all of this South American stuff he could get his hands on (not much) and making elastic waistbands and garters, soles and heels, false teeth, and all kinds of surgical trusses, belts, bandages and so on. The market for rubber was soon insatiable, particularly when Hancock and partner Chas. Macintosh spread it between sheets of cotton and invented the raincoat. So they wrote to the authorities saying, Let's grow this stuff in our Eastern colonies. Make a million, right? The silence from Kew Royal Botanic Gardens (whose job such transplantations were) was deafening.

Turned out the man in charge there, William Hooker, was more concerned with a different tree, from the same end of the world, known as the cinchona, from whose bark quinine could be extracted. Point being that British imperial administrators and military types out in the steamier parts of the globe were dropping like flies from the effects of malaria. Harrumph. Quinine would put everybody back on their feet, so the sun could continue never to set on the Empire. Pip pip. In 1852 the British government got a formal request to fund an expedition to pick up some cinchona seedlings, so Kew could nurture them till they were strong enough to be replanted in India. Alas, the little trees failed to grow well enough to solve the problem.

Meanwhile science wasn't coming to the rescue, in the person of William Perkin, a chemist who noodled away for several weeks in 1856 trying to make quinine chemically. He finally came up with some black gunk that was definitely not quinine. So Perkin chucked it down the sink, saw what it did to the water and became a millionaire almost overnight, because he had accidentally invented the world's first aniline artificial dye. The raw material Perkin was using was the filthy-muck gaslight-manufacture by-product: coal tar, about which I have spoken before. Available by the ton, thanks to James Watt's sidekick, William Murdock, who kind of stole the idea of gaslight from Archibald Cochrane, eighth earl of Dundonald and amateur experimenter. Who produced coal-gas while making pitch to spread on navy ships' hulls to save them from boring teredo seaworms or something. The navy turned his pitch down (in both senses) and ruined him.

Meanwhile science wasn't coming to the rescue.

Ironically, his son Thomas, the ninth earl, ended up a British navy admiral. This was after a checkered career: head of the Chilean navy, head of the Brazilian navy and head of the Greek navy. Thomas was also the inventor of the "Secret War Plan." Secret to this day. Cochrane claimed that his plan was capable of destroying any fleet or fortress in the world. In 1811 the Secret Plan was investigated for the British government by a Secret Committee, who turned it down on the wimpish grounds that it was "infallible, irresistible, but inhuman." So we'll never know.

One of the committee milquetoasts was William Congreve, whose own invention, the Congreve rocket, was to establish him in song and story. Well, song. As in "rocket's red glare," for it was hundreds of Congreves that we Brits launched against Fort McHenry in 1814, exciting young Francis Scott Key to pen the present American national anthem. The music for which was, strange to tell, the work of an Englishman, John Stafford Smith, organist at the Chapel Royal. Back in the 1770s Smith was top of the charts with hits like "Flora Now Calleth Forth Each Flower." He was also more or less the first musicologist. Smith's boss at the chapel was composer Samuel Arnold, whose trick was to put together compilations of other people's stuff, add a bit of his own and do very nicely. At various times, Arnold was director of music at Covent Garden and Drury Lane. Both theaters also employed the Spielberg of the period, David Garrick, who introduced the first high-tech special effects to the stage, and realism to acting.

An aristo patron of Garrick was Lady Dorothy Savile, a dab hand at caricatures, whose husband Lord Burlington was a mover and shaker in the art world. Burlington's live-in protégé (and the guy who taught Lady D. to draw) was William Kent. There are those who think Kent was a third-rate painter and a second-rate architect but a first-rate gardener. Well, maybe. His architectural magnum opus was Holkham Hall in Norfolk, said to be the first time an English architect had designed a house, interior decor and furniture all in one. And people either love it or hate it.

The owner of the hall was Thomas Coke, earl of Leicester, who in 1822 at the age of 69, widower and father of three, married for a second time and had six more. A man of breeding, you might say. Which he also made popular among farmers, with regard to sheep, pigs and cows. All part of the agricultural revolution Coke helped to spearhead with other fancy practices such as crop rotation, turnips (they were used to feed livestock in winter) and clover (upped the yield because it nitrogenized the soil, although they didn't know it). Coke got many of his best ideas from people like Jethro Tull, whose 1731 book on husbandry was a rave seller in Britain and, 20-odd years later, France.

Which is where one of Tull's most avid fans was Voltaire, who went on to apply Tull's principles to his retirement plot at Ferney in Switzerland. This was well after the death of Voltaire's greatest love (out of many): Emilie du Châtelet, with whom he had spent a few happy years' bucolic intellectual idyll after they met in 1733 and recognized a common passion (for Newton). She was learning algebra at the time, and for a while the three of them (she, Voltaire and the algebra teacher) lived in a kind of *ménage à* $x + y + z$ in Emilie's chateau in Champagne. Then *Z* left on a trip, returning two years later in 1737, via Basel, where he picked up a young student who turned out to be such a lout that Emilie and Voltaire fell out with both of them. By this time Voltaire (like everybody else in France) was finding *Z* arrogant to a degree. Not surprising, given where *Z* had just been.

You remember I said one of those two French expeditions, headed by La Condamine, went south to Peru to work on geodetic matters? Well, *Z* (otherwise known as Pierre-Louis Moreau de Maupertuis) was the guy who went north to measure the other meridian, up in Lapland.

Wonders, *continued from page 125*

izer, from ammonia and carbon dioxide. The high explosives of the military—TNT in World War I, mixes of RDX and TNT in World War II, and the newer, more complicated explosives of today—are usually produced in such plants as well, fed by natural gas or oil. The organic molecules chosen as major components differ from one explosive to another, as developers seek improvements in energy, sensitivity, uniformity and overall costs.

The first high explosives were nitroglycerine and guncotton, a whole family of polymers, the nitrocelluloses. Alfred Nobel found how to tame the fluid nitroglycerine, powerful but impractically sensitive, by absorbing and diluting it into an earthy matrix. Dynamite in a new edition—some tamed by high-tech variants of kitty litter—is still in peacetime use, but the up-to-date explosive widely chosen in mine, quarry and woodland is the popular garden fertilizer, ammonium nitrate, dissolved in tiny water droplets, then emulsified in an oil base: it ships looking like big plastic-wrapped sausages—safe, simple to use and cheap.

The truly dark side of the gardener's nitrate granules was learned in pain. As World War I ended, the first Haber-Bosch ammonia synthesis plant closed. It had helped supply the nitrogen needs of warring Germany; its large store of ammonium nitrate was piled in an open field nearby. Once economic chaos eased, the managers sought to regain the space, perhaps sell the fertilizer. In 1921 they drilled many holes into the pile and placed explosive charges within to break it up for removal. Instead the whole mass detonated, and a huge blast of 4,500 tons, the largest to that time, killed some 600 people in the Oppau area!

The lesson was grim but not yet final. In 1947 two ships laden with "fertilizer-grade" ammonium nitrate exploded at kiloton scale in Texas City. The deliberate detonation in Oklahoma City of four tons of that compound again signaled its dual nature—and indeed our own.

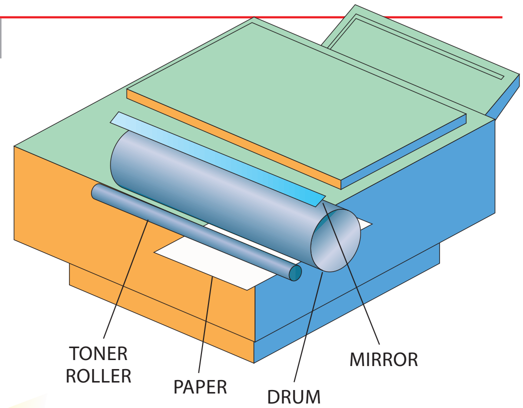
Nuclear explosives work on a wholly different scale; energy yields grow a millionfold, power doubling. Everyone knows our species cannot endure the full military use of fission and fusion. Our country has chief historical responsibility among the nations; do we bear it well today?

WORKING KNOWLEDGE

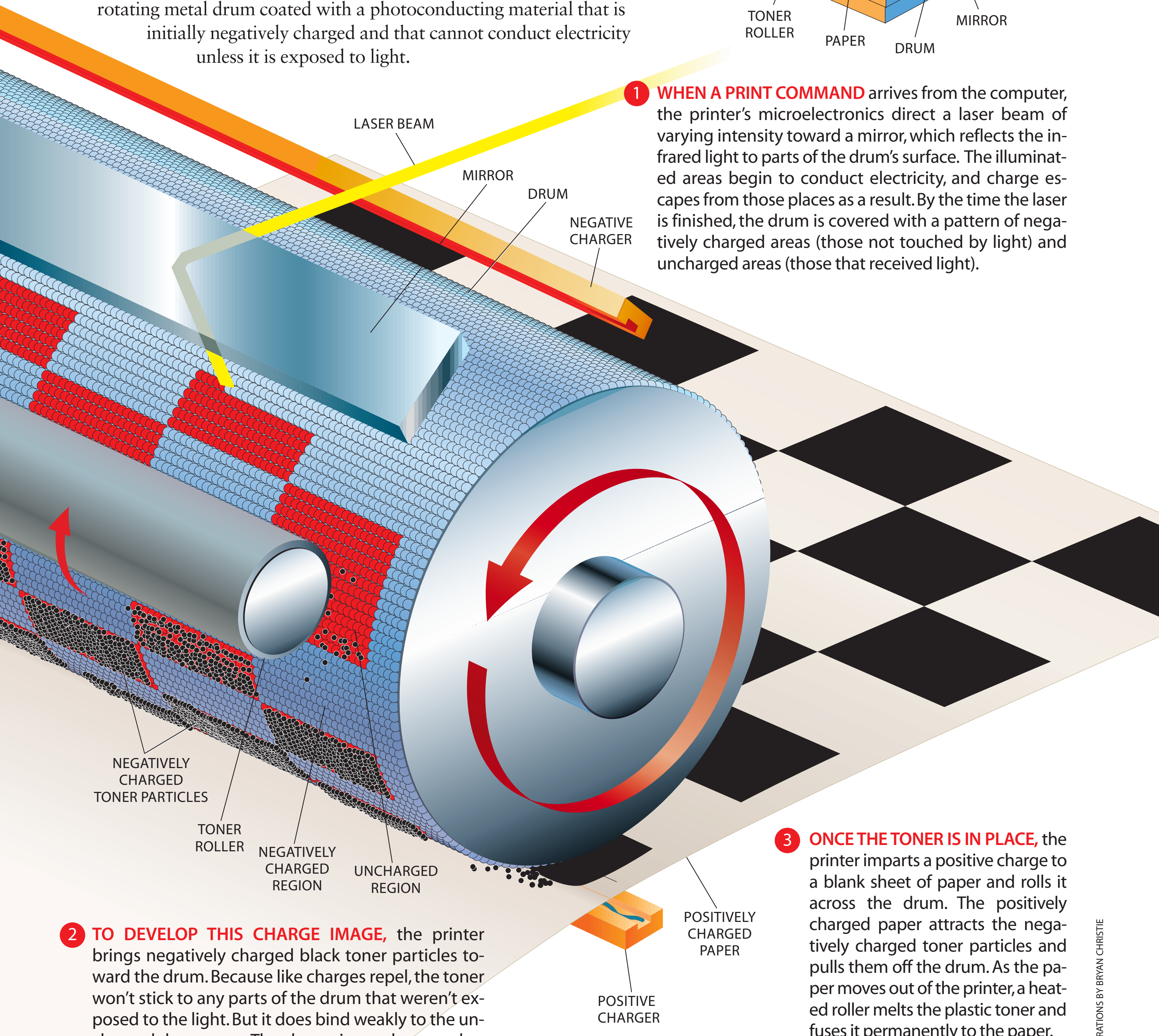
LASER PRINTERS

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

A laser printer combines the printing technology of a xerographic copier [see Working Knowledge, October 1996] with a small laser light show. The printer's main component is a rotating metal drum coated with a photoconducting material that is initially negatively charged and that cannot conduct electricity unless it is exposed to light.



1 WHEN A PRINT COMMAND arrives from the computer, the printer's microelectronics direct a laser beam of varying intensity toward a mirror, which reflects the infrared light to parts of the drum's surface. The illuminated areas begin to conduct electricity, and charge escapes from those places as a result. By the time the laser is finished, the drum is covered with a pattern of negatively charged areas (those not touched by light) and uncharged areas (those that received light).



2 TO DEVELOP THIS CHARGE IMAGE, the printer brings negatively charged black toner particles toward the drum. Because like charges repel, the toner won't stick to any parts of the drum that weren't exposed to the light. But it does bind weakly to the uncharged drum areas. The charge image has now become an ink image.

3 ONCE THE TONER IS IN PLACE, the printer imparts a positive charge to a blank sheet of paper and rolls it across the drum. The positively charged paper attracts the negatively charged toner particles and pulls them off the drum. As the paper moves out of the printer, a heated roller melts the plastic toner and fuses it permanently to the paper.

ILLUSTRATIONS BY BRYAN CHRISTIE