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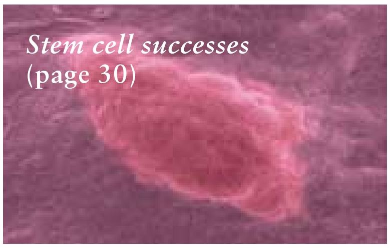
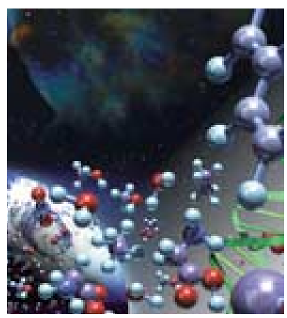
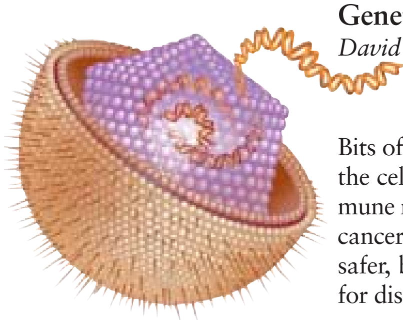
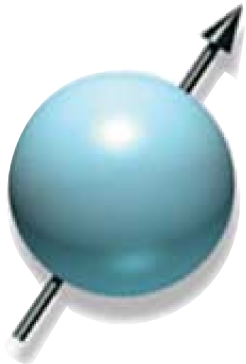
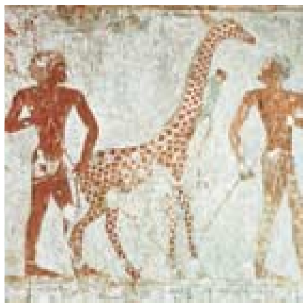


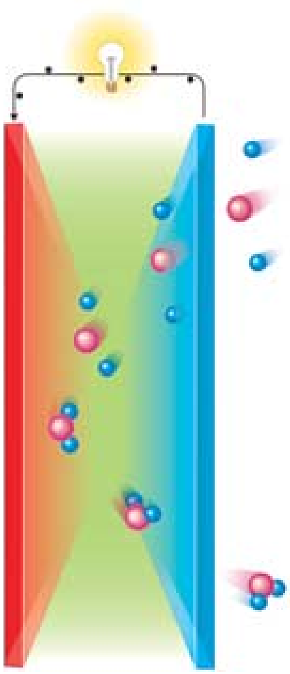
Stem cell successes (page 30)











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About the Cover
Many organic raw materials that helped life evolve may have been transported from space in the ice and dust of passing comets. Image by Alfred T. Kamajian.

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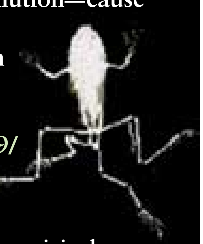


Check every week for original features and this month's articles linked to science resources on-line.

FROM THE EDITORS

A Generation of Genius

"We are Science Past!" proclaimed the resurrected Benjamin Franklin, with an upstage wave toward a similarly lively Isaac Newton, Galileo, Copernicus, Charles Darwin and Albert Einstein. Gazing through his bifocals at the 1,200 high school students gathered from around the world in the Pennsylvania Convention Center, Ben concluded, "You are Science Future!"

So began the grand award ceremonies at the Intel International Science and Engineering Fair (ISEF) this past May in Philadelphia. Watching the costumed actors from the darkened wings, where I waited to present the Earth and Space Sciences prizes, I reflected that art was again loosely imitating life. The week before, I had been in Washington, D.C., for the presentations of the National Medals of Science and Technology. (Our March 1999 issue and our Web site, www.sciam.com, have reports on the medalists and their accomplishments.) Of course, there's nothing Science Past about Bruce Ames, Denton Cooley or any of the other medalists, whose contributions are ongoing. Better to call them Science Present. Still, the intergenerational comparison was impossible to ignore.


COURTESY OF INTEL

BEN FRANKLIN welcomes his latest, youngest colleagues.

In case you haven't visited a high school science fair recently, the projects at the upper tiers have grown tremendously in sophistication; they are a long way from tabletop volcanoes and insect collections. Consider the titles of these winning projects at ISEF: "Dynamics of Energy Transformations at the Molecular Interface," "Prevention of Retroviral Assembly by Expressing Mutant GFP-Capsid Fusion Genes," "Design and Construction of an Inexpensive Automated Device to Determine Atrial Fibrillation in the General Population." Any of them would be at home in a professional journal. And although they were among those singled out for prizes, their ambition and intelligence were alive in every project on exhibit.

The Columbine High School massacre is only a few weeks old as I write this, and people are still desperate for explanations of how two boys could plot and commit mass murder. Some valid points are being made about the distinctive hazards and temptations of growing up today. Yet too much of what's said and written verges on hysterical generalization. In a search for easy answers, some commentators are forgetting how ugly the emotions that churn in places like high schools have always commonly been. My view of the current generation of teens is not so dark, but then I have seen it brightened by the likes of the students at these science fairs. At ISEF, I had the chance to tell them that they are the best there is. What I forgot to add was that they just might be the best there ever was.

John Rennie

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

LETTERS TO THE EDITORS

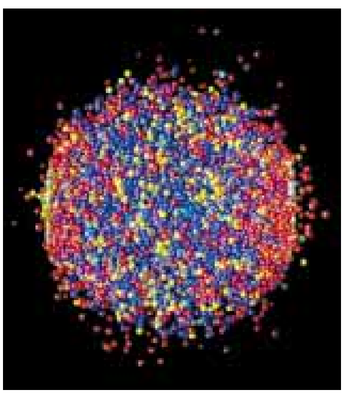
Madhusree Mukerjee's article on the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory ["A Little Big Bang," March] alarmed several readers, such as Michael Cogill of Coquitlam, B.C. "I am concerned that physicists are boldly going where it may be unsafe to go," writes Cogill, who worries that creating stuff that has not to anyone's knowledge existed since the early universe—namely, a quark-gluon plasma—could result in a catastrophe. "What if they somehow alter the underlying nature of things such that it cannot be restored?" he asks. Another reader wondered whether the RHIC experiments could result in miniature black holes (*below*).

BLACK HOLES AT BROOKHAVEN?

Thank you for the article by Madhusree Mukerjee entitled "A Little Big Bang" [March]. In the 1970s Stephen W. Hawking postulated that in the early moments of the big bang, miniature black holes would have been present. Although they no longer exist in our region of the universe, such mini black holes could be created by smashing a proton into an antiproton with enough energy. If one were created near a large congregation of mass and if it started absorbing that mass before exploding, the black hole could reach a relatively stable half-life and thus continue to grow. If this happened on the earth, the mini black hole would be drawn by gravity toward the center of the planet, absorbing matter along the way and devouring the entire planet within minutes.

My calculations indicate that the Brookhaven collider does not obtain sufficient energies to produce a mini black hole; however, my calculations might be wrong. The only way to determine the energy density at which a mini black hole would be created as an intermediary step to the type of explosion depicted in your article is to build a collider and do the experiment. Is the Brookhaven collider for certain below the threshold?

WALTER L. WAGNER
via e-mail



FIREBALL, resulting from heavy ion collision, may reveal primordial plasma.

DATA: KLAUS KINDER-GEIGER AND RONALD LONGACRE; VISUALIZATION: BALLARD ANDREWS, MICHAEL MCGUIGAN AND GORDON SMITH *Brookhaven National Laboratory*

Frank Wilczek of the Institute for Advanced Study in Princeton, N.J., replies:

Whenever we explore new physical (or chemical, or biological) phenomena, questions like Cogill's arise regarding whether we might unwittingly trigger some catastrophe. For example, in the early days of the Manhattan Project, Fermi and others carefully considered whether a nuclear explosion might ignite the atmosphere. Scientists must take such possibilities very seriously—even if the risks seem remote—because an error might have devastating consequences. In the case of the Brookhaven RHIC, dangerous surprises seem extremely unlikely. First, nuclear collisions with larger energies take place regularly as cosmic rays rain down on our atmosphere—so if a disaster were possible, it would have already occurred. Second, related regimes have been explored in detail, and so we have substantial evidence that our theoretical framework for understanding what will happen is reliable. Although we cannot calculate the consequences in complete detail, we can distinguish credible from incredible scenarios.

The idea that mini black holes will be formed, as Wagner suggests, definitely falls in the latter category. The energy densities and volumes that will be produced at RHIC are nowhere near large enough to produce strong gravitational fields. On the other hand, there is a speculative but quite respectable possibility that subatomic chunks of a new stable form of matter called strangelets might be produced (this would be an extraordinary discovery). One might be concerned about an "ice-9"-type transition, wherein a strangelet grows by incorporating and transforming the ordinary matter in its surroundings. But strangelets, if they exist at all, are not aggressive, and they will start out very, very small. So here again a doomsday scenario is not plausible.

DEFENDING DAWKINS

Reading Melvin Konner's review of *Unweaving the Rainbow,* by Richard Dawkins ["One Man's Rainbow," Reviews and Commentaries, March], I was enticed to buy the book immediately. Konner's account sounded so unbelievable that I had to find out for myself. My intuitive reaction guided me correctly—Dawkins is not the man described by Konner. Why has Konner missed the sophistication and knowledge Dawkins brings to the appreciation of wonder in the world of scientists? The respect Dawkins has for people's integrity enables him to recognize their despair when learning about the demystification of their beliefs by scientific discoveries. Rather than joining the charlatans in their weaving of superstitious veils, Dawkins unveils the depths and cosmic dimensions that permeate our existence. A monumental accomplishment indeed.

WILLIAM P. FROST
Department of Religious Studies
University of Dayton

BIOWEAPONS RESEARCH

In his report "Facing an Ill Wind" [News and Analysis, April] on biological terrorism, Tim Beardsley errs in stating that I have "done experiments with simulated weapons and was unable to achieve good dispersal." This statement implies that Sandia National Laboratories has been disseminating biological materials in order to understand the phenomena associated with the militarization of those materials for weapons. Readers might erroneously conclude that Sandia is aerosolizing biological materials for dispersal into the environment, thus violating the Biological Weapons Convention (BWC), which completely prohibits experiments related to the use of biologics in offensive weapons. In truth, Sandia, under contract with the U.S. Department of Defense's Biological Defense Research Program, has employed aerosol experts at other facilities to aerosolize small amounts of pollen and nonpathogenic organisms into a BL2-safety-level cabinet to assess the fluorescent properties of these materials. This work is in full compliance with the BWC.

ALAN P. ZELICOFF
Sandia National Laboratories

DEMONS AND DRAGONS

In his article "The Komodo Dragon" [March], Claudio Ciofi indicates that the name *buaja darat* (land crocodile) is descriptive but not accurate because monitor lizards such as the Komodo are not crocodilians. He goes on to add that the name *biawak raksasa* (giant monitor) is "quite correct." Actually, this, too, is incorrect, in the author's terms anyway. The term *raksasa* is derived from the Sanskrit word for "ogre" or "demon," and monitors, we are certain, are not demons. Incidentally, Komodos aren't dragons either, a fact that the author fails to note.

MURLI NAGASUNDARAM
Department of Computer Information Systems
Boise State University

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. Letters may be edited for length and clarity. Because of the considerable volume of mail received, we cannot answer all correspondence.

ERRATUM

In the caption on page 48 ["The 1998 National Medal of Technology," March], computer scientists Dennis M. Ritchie and Kenneth L. Thompson were misidentified. Ritchie is standing in the photograph; Thompson is seated. We regret the error.

SCIENTIFIC AMERICAN

Sandra Ourusoff
PUBLISHER
212-451-8522
sourusoff@sciam.com

NEW YORK
Thomas Potratz
ADVERTISING DIRECTOR
212-451-8561
tpotratz@sciam.com

Timothy W. Whiting
SALES DEVELOPMENT MANAGER
212-451-8228
twhiting@sciam.com

Randy James
212-451-8528
rjames@sciam.com

Stuart M. Keating
212-451-8525
skeating@sciam.com

Wanda R. Knox
212-451-8530
wknox@sciam.com

DETROIT
Edward A. Bartley
MIDWEST MANAGER
248-353-4411 fax 248-353-4360
ebartley@sciam.com

CHICAGO
Randy James
CHICAGO REGIONAL MANAGER
312-236-1090 fax 312-236-0893
rjames@sciam.com

LOS ANGELES
Lisa K. Carden
WEST COAST MANAGER
310-477-9299 fax 310-477-9179
lcarden@sciam.com

SAN FRANCISCO
Debra Silver
SAN FRANCISCO MANAGER
415-403-9030 fax 415-403-9033
dsilver@sciam.com

DALLAS
THE GRIFFITH GROUP
972-931-9001 fax 972-931-9074
lowcpm@onramp.net

CANADA
FENN COMPANY, INC.
905-833-6200 fax 905-833-2116
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EUROPE
Roy Edwards
INTERNATIONAL ADVERTISING DIRECTOR
Thavies Inn House, 3/4, Holborn Circus
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+44 171 842-4343 fax +44 171 583-6221
redwards1@compuserve.com

FRANCE
Christine Paillet
AMECOM
115, rue St. Dominique
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MARKETING
Laura Salant *MARKETING DIRECTOR*
212-451-8590
lsalant@sciam.com

Diane Schube *PROMOTION MANAGER*
212-451-8592
dschube@sciam.com

Susan Spirakis *RESEARCH MANAGER*
212-451-8529
sspirakis@sciam.com

Nancy Mongelli *PROMOTION DESIGN MANAGER*
212-451-8532
nmongelli@sciam.com

NEW YORK ADVERTISING OFFICES
415 MADISON AVENUE, NEW YORK, NY 10017
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Verlagsgesellschaft mbH
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Éditions Belin
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LE SCIENZE
Le Scienze
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20121 Milano, ITALY
tel: +39-2-29001753
redazione@lescienze.it

Investigacion y Ciencia
Prensa Científica, S.A.
Muntaner, 339 pral. 1.ª
08021 Barcelona, SPAIN
tel: +34-93-4143344
precisa@abaforum.es

Majallat Al-Oloom
Kuwait Foundation for the Advancement of Sciences
P.O. Box 20856
Safat 13069, KUWAIT
tel: +965-2428186

Swiat Nauki
Proszynski i Ska S.A.
ul. Garazowa 7
02-651 Warszawa, POLAND
tel: +48-022-607-76-40
swiatnauki@proszynski.com.pl

日経サイエンス
Nikkei Science, Inc.
1-9-5 Otemachi, Chiyoda-ku
Tokyo 100-8066, JAPAN
tel: +813-5255-2821

Svit Nauky
Lviv State Medical University
69 Pekarska Street
290010, Lviv, UKRAINE
tel: +380-322-755856
zavadka@meduniv.lviv.ua

ΕΛΛΗΝΙΚΗ ΕΚΔΟΣΗ
Scientific American Hellas SA
35–37 Sp. Mercouri St.
Gr 116 34 Athens GREECE
tel: +301-72-94-354
sciam@otenet.gr

Ke Xue
Institute of Scientific and Technical Information of China
P.O. Box 2104
Chongqing, Sichuan
PEOPLE'S REPUBLIC OF CHINA
tel: +86-236-3863170

50, 100 AND 150 YEARS AGO

SCIENTIFIC AMERICAN

JULY 1949

STRESS AND SCHIZOPHRENIA—"The adrenal cortex seems to be involved in schizophrenia and perhaps in other mental conditions. A sample group of schizophrenic patients showed a striking inability to respond with enhanced steroid output to stress tests, despite the fact that their normal steroid secretion was little different from that of the general population. The adrenal cortex in the schizophrenic thus generally cannot change its activity with changing situations. It may be that chemical deficiencies of this kind, perhaps genetically determined, make some persons more vulnerable than others to the stresses of living."

LUNAR LANDSCAPE—"The most plausible explanation of the craters of the moon appears to be that they were created by the cataclysmic impacts of great meteorites. To draw a more definite conclusion about this hypothesis, we can draw on the knowledge accumulated during the recent war about craters blasted in the ground by bombs, mines and artillery shells. It becomes clear that the only type of crater that corresponds to the ones on the moon is the simple explosion pit formed by a single application of explosive power. Such a pit always has the same general form."

JULY 1899

RAILWAYS UNDERGROUND—"The East River Tunnel is merely a part of the extensive improvements contemplated by the Long Island Railroad. From the station near City Hall Square, Brooklyn, the tunnel will extend to the present Flatbush Avenue station, where it will be 18 feet below the street level [*see illustration*], and to the Franklin Avenue station. The cars to be used in the tunnel will be about the same size as the Brooklyn Bridge cars, about 50 feet in length, and each will be capable of seating 60 passengers."

TESTING HULL DESIGNS—"The value of towing experiments upon small scale models of ships for the purpose of deducing the resistance of a full-sized ship was demonstrated by the late Mr. William Froude, in about 1870. The Construction Bureau of our Navy Department completed an experimental basin, 470 feet in length, in the latter part of last year, and the special machinery and apparatus have now been completed and installed. A towing carriage, driven by electricity, carries the recording apparatus. The dynamometric apparatus is designed to avoid entirely the use of levers or other devices involving the possibility of friction, and here again electricity is enlisted. The recording drum is fitted with apparatus for recording the time and distance, by which the amount of pull on a hull can be determined."

The new subway for Atlantic Avenue in Brooklyn

IVORY SUPPLY—"It is clear that African ivory is likely to become gradually scarcer and scarcer; and if there were no other source of supply this beautiful substance would apparently soon reach a prohibitive price. As a matter of fact there exists in the frozen tundras of Siberia a supply of ivory which will probably suffice for the world's consumption for many years to come. This ivory is the product of the mammoth (*Elephas primigenius*), a species nearly allied to the Indian elephant."

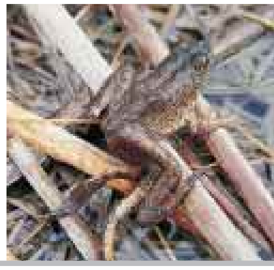
JULY 1849

MEAN TEMPER, BAD ODOR—"It is a fact well known to those who have visited the mountainous regions of Syria, Palestine, and the Peninsula of Sinai, that the camel is as serviceable on rough mountain paths as in the moving sand of the desert. The tough soles of the camel's feet are affected neither by the burning sand nor by sharp-edged stones. There is no reason why the camel should not be as serviceable to man on the Prairies of Texas and the mountain region of Mexico, New Mexico, and California, as in the corresponding tracts of the Old World." [*Editors' note: In 1855 Secretary of War Jefferson Davis was authorized to buy camels "for military purposes" in an unsuccessful experiment.*]

RAW SEWAGE AND FOOD—"The dread of cholera has completely cured people of lobster eating. Two thousand were thrown overboard the other day at Gloucester, Mass."

GOLDEN AGE OR GREENER GRASS?—"It is now the fashion, says Macauley, to place the golden age of England in times when even noblemen were destitute of comforts, the want of which would be intolerable to a modern footman. We too, in our turn will be envied. It may be in the twentieth century that the peasant of Dorsetshire may think himself miserably paid with 15 shillings a week; that the laboring men may be as little used to dine without meat as they now are to eat rye bread; that sanitary police and medical discoveries may have added several more years to the average length of human life."

NEWS AND ANALYSIS



IN FOCUS

SEEKING COMMON GROUND

Building a new generation of gargantuan telescopes gets mired in environmental and native cultural issues

In the mid-1950s a group of astronomers funded by the National Science Foundation showed an interest in a mountain in southwest Arizona called Kitt Peak. Its clear, dry air, removed from Tucson's city lights, made it among the most promising sites being considered for the first national observatory. The Tohono O'Odham, however, refused a request to investigate the suitability of the site atop one of their most sacred mountains. An enterprising anthropologist at the University of Arizona suggested that the tribal council be invited to look through a telescope in the Steward Observatory on the university campus. Peering through the 36-inch-diameter (about one-meter-wide) telescope, the tribal elders had trouble containing their excitement. One after the other, each of the men would stare through the eyepiece and then move his head to view the bright moon glow through the top of the dome. Shortly thereafter, the tribal council voted to reverse itself and let the astronomers proceed. The members "were totally charmed by the people they called the men with long eyes," says Frank K. Edmondson, professor emeritus of astronomy at Indiana University, who chronicled a history of the project in his book on the U.S. national observatories.

BARNEY MAGRATH

"PIMPLES" ON MAUNA KEA is the way some Hawaiian residents have referred to Hawaii's world-class observatories that dominate the barren summit area.

Gone are the days when astronomers were granted free run of an isolated mountaintop for a mere peek through an eyepiece. Now astronomers who hope to peer deeper into the universe find themselves running into legal headaches on earth—which threaten to delay or scuttle massive projects.

The University of Arizona, which so deftly helped to negotiate an accord with the Tohono O'Odham, has found itself mired for more than a decade in a public-relations nightmare involving new telescopes on Mount Graham in southeastern Arizona. The debacle has set it against environmentalists trying to defend an endangered subspecies of red squirrel and against a group of Apaches trying to protect a holy site. The university blustered through only by weathering numerous lawsuits and by getting congressional exemptions that allowed it to circumvent the Endangered Species Act, the National Environmental Policy Act and a federal court order. For the moment, the astronomers have won. Construction was completed in the early 1990s on the 1.8-meter Vatican Advanced Technology Telescope and the 10-meter Heinrich Hertz submillimeter telescope. And work is moving ahead on the twin 8.4-meter mirrored Large Binocular Telescope.

Balancing the needs of astronomy with environmental and cultural issues has moved to the forefront on perhaps the world's most coveted astronomical site, the 11,288-acre (4,571-hectare) science reserve atop Mauna Kea on Hawaii's Big Island. The Board of Regents of the University of Hawaii is scheduled to vote by the end of this year on a plan that will establish a framework for development on the mountain for the next 20 years. Mauna Kea, whose summit area is leased by the university from the state, could become the location for some of the most ambitious projects of the new century, including a 25- to 50-meter Next Generation Large Telescope and an optical interferometer array that could consist of up to 30 telescopes.

The Mauna Kea advisory committee, a 23-member panel set up by the university to obtain public input, voted in May by a roughly two-to-one margin to endorse the plan. But the two loudest dissident voices on the committee—the Sierra Club and Ka Lahui Hawaii, a Hawaiian sovereignty group—have blasted the plan as insufficient to protect the mountain from overdevelopment.

RARE INSECTS such as the Wekiu bug* (Nysius wekiuicola) *should be protected from overdevelopment atop Mauna Kea, say environmentalists.

The master plan would create an astronomy precinct in which 600 acres, or some 5 percent, of the science reserve managed by the university could be used by astronomers. The 13 Mauna Kea observatories currently occupy about 60 acres. Nelson Ho, a regional vice president for the Sierra Club Hawaii, has called for a moratorium on new telescopes until a more acceptable approach can be devised that puts a halt to what he calls the "industrialization" of the Mauna Kea summit. Ho says the Sierra Club is considering filing a lawsuit to stop any new projects. The top of the mountain is home to rare insects, including the Wekiu bug, which survives by eating insects blown up from the lowlands. Mauna Kea is also considered in oral Hawaiian traditions to be the first-born child of the gods of the sky and the earth, the most sacred place in all the islands.

The University of Hawaii hurriedly commissioned the new master plan after a state audit last year found that the university's management of the mountaintop was "inadequate to ensure protection of natural resources." The audit's findings, many of which were contested by the university, made assertions about neglect of historical preservation and cultural sites, damage to the habitat of the Wekiu bug and failure to remove trash and equipment, some of which had lingered for decades.

The advisory committee voted to recommend that no new construction be started until the new plan is approved and funded by the university's Board of Regents, perhaps later this year. Astronomers and observatory directors have welcomed the advisory committee, which has brought together Hawaiian cultural groups, university officials, and even skiers and hunters who use the mountain. "Throwing every point of view on the committee may result in a catfight, but it's when people are left out of the process that you run into problems," says Frederic Chaffee, director of the W. M. Keck Observatory. Privately, though, some members of the Hawaiian astronomy community fret about the effect a persistently tumultuous political environment may have on future projects. "Astronomy on the Big Island could go the way of the sugarcane industry," says one observatory director. The impact of Mauna Kea astronomy on the Hawaiian economy in both direct and indirect revenues is estimated to be $142 million annually.

The new master plan would place limits on the size, location and even color of new observatories, an attempt to help them blend into their surroundings and to preserve Wekiu habitat, archaeological sites and other culturally important areas of the mountaintop. "This plan puts severe constraints on the future of astronomy, and some would say too much," says Jeffrey Overton, project manager for Group 70 International, the Honolulu consulting firm that drafted the plan. (Group 70's work was paid for from money the Keck Observatory contributed to an infrastructure fund as part of its agreement with the university to build the Keck II telescopes.) The plan also contains controversial provisions that might limit vehicle access to the summit and might require the observatories to pay a part of the cost of hiring rangers and implementing other measures to improve management of the reserve.

Negotiations about the future of Mauna Kea come at a time when management of the astronomy program finds itself in disarray. The university is trying to build one of the world's top astronomy departments to take advantage of the free telescope time it receives from the observatories. But no one seems to want the political headaches that come with the job. In April, Richard Ellis, a noted cosmologist from the University of Cambridge, turned down an offer to head the university's Institute for Astronomy. Although he would have welcomed the chance to mold its astronomy effort, he did not wish to deal with the job's myriad political and administrative responsibilities—which would include coping with land-use issues on Mauna Kea.

But guiding astronomy programs—and the Big Science projects that come with them—may now require leaders to take on the mantle of the scientist-diplomat. Hawaii might study closely the Mount Graham experience. "The University of Arizona came across as saying, 'We're the big guys, we can do what we feel like,'" notes Chaffee, who was a spectator of the Mount Graham controversy while head of the University of Arizona's Multi-Mirror Telescope. But Chaffee points out that this attitude has the "potential for poisoning the climate for science." The bad blood generated over Mount Graham has meant that the issue will fester for years and could block any new telescope on the mountain. By necessity, leaders of astronomy may be forced to become Kissingers as well as Galileos. *—Gary Stix*

INTERNATIONAL SCIENCE

MAKE SCIENCE, NOT WAR

For Sarajevo's scientists, peace is proving as challenging as war

To reach the observatory, we drove past the gutted motel, climbed over the fallen lamppost and walked past the trenches. Muhamed warned me to follow in his footsteps; the area hadn't been searched for mines yet. Over the stubs of trees we could see Sarajevo stretched out below us, a lovely sight for a gunner. The observatory was littered with shiny glass from shattered telescopes, an old *Nature* cover, a green plastic turtle Muhamed's daughter used to play with when visiting. "Some scraps of memory," he remarked. "I worked here 20 years."

Three years after the end of siege, Sarajevo is once again a fairly normal European city. But scientific research is still just a memory, and many people worry that it might always be. "Higher education never has been a priority in reconstruction efforts," says Wolfgang Benedek of the World University Service, an Austrian-based advocacy group.

GEORGE MUSSER

SARAJEVO OBSERVATORY was near one of the city's many front lines.

Prewar Bosnia and Herzegovina was no scientific powerhouse, but it had respectable accomplishments, particularly in regional archaeology and electrical engineering. The amateur astronomy association, led by Muhamed Muminović, my guide, was the most prolific in Yugoslavia and had done professional-level work.

The continued operation of the University of Sarajevo in wartime was a source of pride, a way for ordinary people to resist ethnic cleansing by Serb forces. Of the prewar enrollment of 23,000 undergraduates, a third pressed on. Bosnian government soldiers occupied one side of the physics and chemistry building while classes were held across the hall. Alma Šahbaz, a student, remembers coming to the science campus one day and hearing Serb soldiers just across the river blasting nationalist music. From the science buildings, the city's defenders replied with muezzin calls. Most classes were moved to the veterinary school, away from the front line. But learning was always dangerous. Students in chemistry labs had to bring their own water—no small order, because water queues often became massacre sites.

For physics professor Kenan Suruliz, reaching classes called for a 40-meter-dash across Sniper Alley. He recalls taking a slightly different route one day. When he arrived at the steps of his building, he heard an explosion and looked back. A mortar had landed on his usual path. Between the exercise and shortage of food, Suruliz lost 35 kilograms (80 pounds). As colleagues fled or died, he had to teach subjects well outside his field. Typically for Sarajevo, his head was in the 20th century and his body in the 14th.

Officials estimate that Bosnian universities overall suffered at least $20 million in physical damage. Seventy percent of professors went into exile. Since the war the demands on these institutions have intensified: young people need to make up lost time, and the country must rebuild its professional classes. The European Union has spent four million euros (about $4 million) on new equipment and staff training. The World University Service coordinates donations of books and equipment, awards small grants for interethnic collaborations and helps Bosnians studying abroad to return.

To ease the intellectual isolation, physicists Arthur Halprin of the University of Delaware and Yves Lemoigne of the Saclay Research Center in France have organized workshops in Sarajevo on neutrinos and on the scientific use of the World Wide Web (attended by, among others, Robert Cailliau, one of the Web's inventors). The latter drew half a dozen students from the University of Banja Luka in the Bosnian Serb Republic—beneficiaries of a short-lived thawing of intercultural relations.

These efforts will do little lasting good without political backing. But leaders have other things on their minds—namely, themselves. In February biology professors went on strike for two weeks because EU grants for their building—the top third of which remains fit only for pigeons—were apparently diverted to lightly damaged departments with political connections. A visitor quickly learns that repeated letters and phone calls to administrators go unanswered and appointments are not kept.

What bothers Halprin is that lethargy pervades the university. When he visited last September, donated journals were still unpacked, on-line subscriptions inactive, a fax machine never plugged in. Halprin's ideas for rehiring exiled faculty ran into petty politics.

The remnants of Sarajevo's scientific community are held together only by an enduring commitment to the city and its multicultural ideals. And even that has eroded. The Kosovo war has shown how fragile people's loyalty has become. If hostilities spread to their country, young Sarajevans say they have no intention of staying and fighting, as they did in 1992. One physics student, scraping by in Paris, captured the ambivalence: "I can't live without Sarajevo, but I hate its stagnancy."

Ivo Šlaus, a physicist at Rudjer Bošković Institute in Zagreb, worries that the opportunity to rebuild science has been squandered. The world's attention and aid are shifting to Kosovo and, perhaps soon, post-Milošević Serbia. Even in 1996 Šlaus told a National Research Council workshop, "It is in many ways too late." That bodes ill for the whole society. Bosnia does not have so many vigorous institutions that it can afford to watch one waste away.

—*George Musser in Sarajevo*

FIELD NOTES

DISCERNING CERN

A hard-hat tour of the world's largest particle accelerator, under construction

One might expect a trip to CERN, the European laboratory for particle physics, to include plenty of talk about quarks, bosons and the rest of the vanishingly small particles that make up our universe. Lately, though, discussions here have focused on much larger objects: the massive industrial cranes, backhoes and tunnel-boring machines being used to move around nearly one million tons of dirt with the goal of pushing back the frontiers of physics.

CERN, located on the French-Swiss border right outside Geneva, is currently home to the world's largest particle accelerator, the Large Electron Positron collider, or LEP. Since 1989 LEP has been creating fast-moving, highly energetic beams of electrons and their antimatter counterparts, positrons, and then smashing the two into each other; specially designed detectors monitor the energy and particles released during the collisions. The electron and positron beams pick up speed and energy as they travel around a circular tunnel 27 kilometers (17 miles) in circumference and 100 meters (330 feet) underground. Four detectors, each several stories tall, intersect the tunnel where the electron and positron beams collide.

Over the years, the LEP detectors have enabled scientists to identify some of the fundamental building blocks of matter that were present right after the big bang. But the collider's days are numbered. The accelerator will remain in service until October of next year, when it will be shut down and dismantled to allow the final phases of construction to proceed on CERN's next-generation experiment, the Large Hadron Collider (LHC).

Due to be switched on in 2005, LHC will be capable of slamming particles (in this case, protons or lead nuclei) together at speeds and energies not possible with LEP. A major goal of the LHC project is to continue the hunt for the elusive Higgs boson. Physicists postulate that space is filled with what they term the Higgs field, and they speculate that subatomic particles like quarks and leptons acquire their masses by interacting with it. The Higgs boson is a particle associated with the field.

But before I can put on a hard hat to check out recent progress on LHC, my host, Neil Calder from CERN's press office, suggests we visit one of the older, smaller LEP detectors so that I can fully appreciate the increased size and power of the new LHC equipment. Calder reminds me to bring my passport—we're off to France to see the detector known as L3 (the proposal for the detector was in the third letter received by the LEP experiment selection committee; the abbreviation "L3" stuck). Our elevator takes us 60 meters underground; stairs will take us even deeper. A narrow hallway opens up to a large chamber—I'd estimate about four stories high—that houses the L3 detector. It is bright red, and Calder rattles off the commonly cited statistic about L3: "40,000 tons of steel—more steel than in the Eiffel Tower."

After this introduction to the modest LEP equipment, I'm ready for LHC. The new accelerator will be housed in the same 27 kilometers of tunnel that LEP occupies now, with the addition of a few short connecting tunnels and four underground chambers for the LHC detectors. Jean-Luc Baldy, head civil engineer on the LHC project, escorts me around the site that will eventually accommodate one such device, known as ATLAS (short for *a toroidal LHC apparatus,* in reference to its doughnut shape).

As we trudge through the muddy terrain in our knee-high boots, Baldy describes the architecture of the underground chamber for ATLAS, which will be big enough to hold a six-story building. Specifically, the chamber will be 35 meters in height and have an essentially rectangular base 30 by 53 meters—some 100 meters below the surface.

Before work on the ATLAS chamber can begin, however, workers must excavate several vertical concrete-lined passageways to shuttle people and equipment down below. Baldy takes me over to where workers are in the early stages of tunneling the largest of these tubes (because of the size of some of ATLAS's parts, one of them must be 18 meters in diameter). Construction of the chamber itself is scheduled to start next spring.

Baldy is clearly anxious about the technical challenges presented by the ATLAS chamber, which will be the first underground cavity of this size built in the type of sediment found at CERN. The rocks here include sandstone and marl, both of which are considerably softer and less stable than bedrock such as granite. Baldy and his team will reinforce the walls of the structure by means of several clever techniques. For instance, 20-meter-long steel rods extending from the exterior of the chamber into the surrounding rock will help stabilize and anchor the walls.

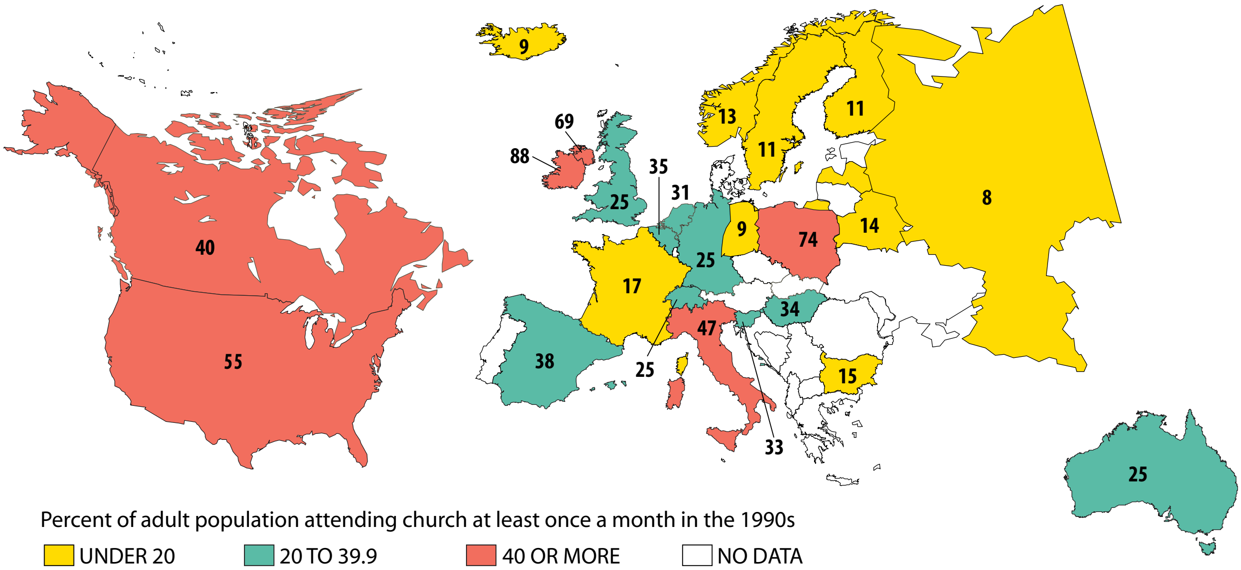
Despite the countless hours he and his crew have spent going over plans, verifying that the scheme will work, Baldy acts like a worried father—apprehensive but proud. On the way back to his office, he explains why he took the job here: "I wanted to work on really big things." —*Sasha Nemecek in Geneva*

CERN PHOTO

CONSTRUCTION OF THE LARGE HADRON COLLIDER at CERN, the European laboratory for particle physics near Geneva, should be completed by 2005.

BY THE NUMBERS

Christian Differences



SOURCE: Ronald Inglehart and Wayne E. Baker, "Modernization, Secularization, Globalization, and the Persistence of Tradition," in the "Millennial Symposium" of the American Sociological Review *(in press). Data are for 1995–1997 except for Ireland, N. Ireland, Italy, Belgium, Canada, the Netherlands, Great Britain, Hungary, France and Iceland, which are for 1990–1991. The former countries of East and West Germany are shown separately.*

So many Americans attend church, according to sociologists Roger Finke of Purdue University and Rodney Stark of the University of Washington, because there is a free market in religion, and a free market promotes competition among denominations for new members. U.S. churches, unlike the established churches of Europe, compete by making themselves more attractive to potential parishioners, and thus membership grows. Finke and Stark estimate that the number of adherents rose from 17 percent of the population in 1776 to about 60 percent today. In 1776 Congregationalists, Episcopalians and Presbyterians were among the leading denominations but lost position because they were ill equipped to compete for new members, particularly on the rapidly expanding frontier. Their well-paid, college-educated ministers were loath to leave comfortable parishes in the East for the rough-and-tumble of the frontier. Furthermore, their scholarly, sometimes dry sermons had little appeal to frontier settlers.

Soon the old-line denominations were eclipsed by the Methodists and the Baptists, who, with their revival meetings and circuit riders, promised life everlasting for the saved and hellfire for sinners. Moreover, their relatively uneducated ministers had a natural rapport with the people, coming as they did mostly from the same class. Methodists were the leading group in the mid-1800s, but as they became more affluent and as their ministers became seminary-trained, their fervor declined, and members who yearned for a more evangelistic faith left to found new churches.

By the turn of the 20th century the Methodists were in decline, but the Baptists retained their fervor and prospered, particularly in the South. Today the Southern Baptist Convention, which has 16 million adherents, is the largest Protestant denomination in the U.S. and, together with other evangelicals, has contributed to the high attendance rate in the U.S.

American Catholics have also contributed to that high rate. Few immigrants from traditionally Catholic lands were initially in the habit of attending mass. To coax them, the priesthood adopted evangelical methods, using a message of personal renewal and their own techniques of revivalism—called the parish mission. Like the Methodist and Baptist circuit riders, the Catholic priests did not pursue affluence and were ready to go wherever the church sent them. They sprang from the same class of people that they served, and their message, given without literary ornamentation, was easily comprehended. The Roman Catholic Church, with its 61 million adherents, is now by far the largest denomination in the U.S.

In Europe, monthly church attendance rates range from a mere 8 percent in Russia to 88 percent in Ireland. The low rate in Russia (and most other former Soviet bloc countries) very likely traces back in part to official suppression of religion during the Communist era. In Ireland (and also Poland) the Catholic Church is popular because it is seen as the defender against foreign enemies. A possible explanation for the differences in other European countries comes from an old theory that holds that Protestants are more likely to fall away from the church because they have given up the highly emotive language and the rich symbolism of Catholicism, which, it is said, serves as a counter to the rationalism of modern science and technology.

Some of the facts are consistent with the theory of church attendance and denomination: Scandinavian countries have small Catholic populations and very low church attendance rates. The former West German state, where Protestants and Catholics both have large minorities, is in the intermediate range, and attendance rates in Italy, a mostly Catholic country, are fairly high. Most others, however, do not fit neatly into this pattern. Spain and Belgium, both traditionally Catholic countries, have intermediate rates, whereas France, also traditionally Catholic, is in the bottom category—not surprising, given its long anticlerical tradition. *—Rodger Doyle (rdoyle2@aol.com)*

RODGER DOYLE

AIDS RESEARCH

DEATH OF A VACCINE?

People with weakened HIV are getting sick, quelling enthusiasm for a live AIDS vaccine

In the late 1980s AIDS researchers began to notice that some of their patients just weren't getting AIDS—despite the fact that they had been infected for roughly 10 years with the human immunodeficiency virus (HIV). The scientists started to hope that such "long-term nonprogressors," some of whom happened to have strains of HIV that were missing some genetic information, might hold the keys to developing an AIDS vaccine.

That hope has now been dampened. At least two long-term nonprogressors have now done just that—progressed toward AIDS. Besides being bad news for other people with HIV who do not yet have symptoms, this turn of events supports other evidence that an AIDS vaccine based on a live form of HIV that is missing one or more genes might not be safe enough to administer to humans.

The most recent report comes from the Sydney Blood Bank Cohort: an Australian man infected more than 17 years ago with what was thought to be a crippled form of HIV and eight people who received transfusions of the man's donated blood (done before blood was routinely tested for HIV). In February the man was diagnosed with an AIDS-related infection of the brain and spinal cord. Two of the recipients of his blood also now have signs of a weakened immune system; of the other six, three are still healthy and three have died from causes not equivocally traced to HIV.

Earlier this year Ronald C. Desrosiers of the New England Regional Primate Research Center in Southborough, Mass.—the scientist who has obtained the most promising results in monkeys of live, attenuated AIDS vaccines—and his colleagues announced that one of the long-term nonprogressors they had followed for more than 15 years was also developing signs of AIDS. The researchers found that the man, who harbors a strain of HIV that lacks a gene called *nef,* had experienced a sharp drop in his T cell count to near the cutoff normally used to designate AIDS.

The man's outcome stands in disappointing contrast to Desrosiers's 1992 observation that a vaccine made of *nef*-missing simian immunodeficiency virus (SIV), which causes AIDS in monkeys, allowed a group of four monkeys to fend off infection completely with a more virulent strain of the virus. The *nef* gene is thought to regulate the ability of SIV and HIV to reproduce.

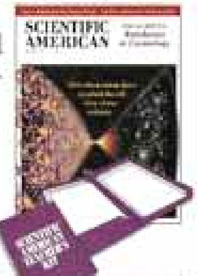
Over the past several years, Desrosiers and his colleagues have announced more encouraging animal results with SIV and HIV vaccines missing all or pieces of up to four genes. But throughout, other investigators, including Ruth M. Ruprecht of the Dana-Farber Cancer Institute in Boston, have noted that SIV vaccines lacking *nef* and other genes can sicken and kill both newborn and adult animals, leading the scientists to raise an alarm about the possible danger of a live, attenuated AIDS vaccine for humans.

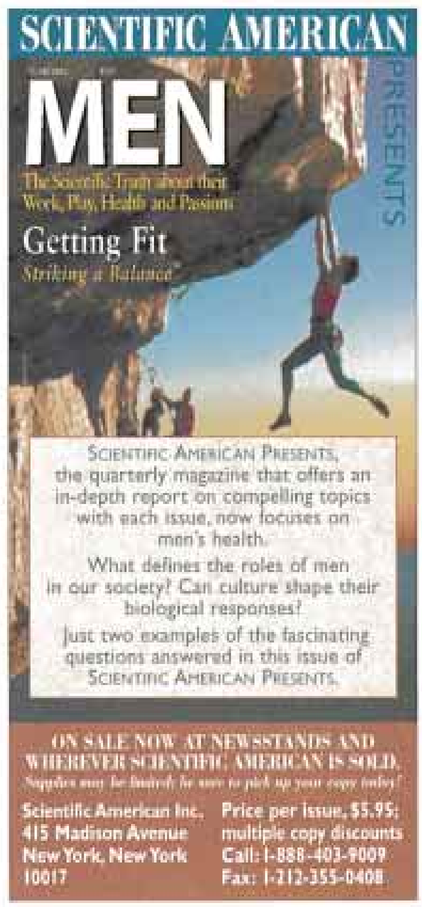
In February, Ruprecht and her coworkers declared that a triply deleted strain of SIV—missing *nef,* a second gene named *vpr* and some other genetic information—caused disease in three of 16 adult monkeys, one of which died of simian AIDS. "Our study indicates that it is not safe to conduct human tests of AIDS vaccines made from live, weakened viruses," Ruprecht warns. "There is a real risk of contracting AIDS from the vaccine itself."

Coupled with the monkey data, the latest reports of illness among people infected with *nef*-deleted strains of HIV are prompting many workers to consider human tests of a vaccine based on live, gene-deleted HIV a moot point. "It will be terribly difficult to conduct clinical trials of even a multiply deleted vaccine in the current climate," says John P. Moore of the Aaron Diamond AIDS Research Center at the Rockefeller University.

But Desrosiers continues to emphasize that to stem the AIDS epidemic, society must be prepared to accept some risks. Last autumn he called for a large-scale placebo-controlled test of the safety of a multiply deleted SIV vaccine in hundreds of monkeys.

Whether or not such a massive study of SIV missing various genes is mounted, Moore says Desrosiers's tests in monkeys have already provided crucial information about the body's immune response to SIV and HIV. "The early experiments looked so good," he comments. "But we can still learn a lot about what constitutes protective immunity against SIV and HIV by studying these viruses in animals." —*Carol Ezzell*





IN BRIEF

Mars Bars

Magnetic patterns in its now cold crust indicate that Mars once had enough heat to spin its iron core and generate a magnetic field, says the Mars Global Surveyor magnetometer team in the April 30 *Science*. The patterns also hint that Mars may have had processes similar to plate tectonics on Earth. Flip-flops in Earth's magnetic field imprint material along spreading ridges, where rising magma pools on either side and then cools. The magnetic reversals and spreading, caused by the motion of crustal plates, create a unique pattern on either side of the ridge. Such symmetry has yet to be seen on Mars, however, so its past tectonics may have been different. —*Christina Reed*

Multilegged Mayhem

At least one culprit has been identified behind some of the deformities seen recently in frogs in the U.S. Stanley K. Sessions and his colleagues at Hartwick College report in the April 30 *Science* that growth of extra legs can result directly from a trematode, rather than from the other suspects, pesticides that may mimic deformity-inducing retinoids. The minute trematodes, called *Ribeiroia,* burrow into the hind limb buds of tadpoles, wreaking havoc with leg growth. The crippled frogs may help their parasitic cargo infect its primary host—when the frogs fail to escape a hungry bird. —*Jessa Netting*

STEVE MASLOWSKI *Photo Researchers, Inc.*

Trematode tricks

Endangered Homo Sapiens

Humans had a brush with extinction, say Pascal Gagneux and his colleagues at the University of California at San Diego in the April 27 *Proceedings of the National Academy of Sciences*. Looking at 1,158 control regions of mitochondrial DNA sequences, which are passed on maternally, the biologists reconstructed and compared the female history in humans, chimpanzees, bonobos and gorillas. Humans have few genetic variations; the small variability suggests a dramatic falloff in human population in the past million years, probably from disease, natural disaster or conflict. —*C.R.*

More "In Brief" on page 30

ANTI GRAVITY

Soyuz Wanna Fly in Space

Anybody who goes anywhere without a roll of duct tape is a fool. This is common knowledge. It's also the second thing I thought of when I heard that a British businessman was angling for a ride on board the Mir space station, which at this point is barely even a mere space station. The first thing I thought of, as always, was my own name: Mirsky. My obsessive-compulsive desire to tack a suffix onto Mir skates through my head each time I see that three-letter word, a reaction that even I begin to find tiresome.

Anyway, the Russians, no longer Red, are in the red—which, after throwing off the shackles of communism, is like having an irony curtain descend on them. And Mir's keeping them there, with its operating costs of about $20 million a month. (In case you're wondering, $20 million converted to rubles equals one really stupid monetary transaction.) They were getting ready to scuttle Mir, skint as they are. But on January 22 they announced that they would keep Mir skyborne until 2002 if private investors would sponsor the station's upkeep.

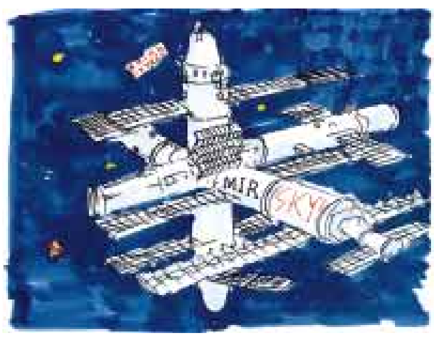
According to wire service reports, a British businessman stepped up with an offer of $100 million, in return for which he would spend a week on Mir. Schemes from the past in which he had allegedly failed to come across with promised funding then surfaced. (The businessman will remain nameless, as *Scientific American*'s lawyers are all at their summer cottages and left strict instructions that they not be disturbed until after Labor Day.) Again according to published reports, he in turn then denied that he was ever going to be giving any money to the Russians. Instead his idea is to spend the week doing some kind of demented space-a-thon, raising money per mile traveled, which would go toward building a hospital.

As this issue went to press, Mir's key problem, the funding to keep flying, was still unsolved. Because the space station is close to my heart, however, I would like to help. And I think I have a plan at least worth considering. For one thing, I don't want to go up there, so that should help keep Mir's skyrocketing costs down. One of the supreme ironies of our time is that in space, there's so little space. If I want to spend a week in a cramped, uncomfortable, moving room that must have accumulated some interesting smells by now, I can do that for the $1.50 entrance fee to the New York City subway. (Trust me, space is not necessarily the final frontier.) For another thing, money is only as good as what you can buy with it. And I have some items I'm ready to donate to the cause, items that might be worth more than money.

Foremost on my list is one of those pens that can write upside down. The packaging even has on it, "Selected by NASA," which would make it perhaps the most reliable piece of equipment on board. The pen could be used, for example, to create a sign saying "Please send oxygen," to be held up to the window in case the space shuttle happened by.

I also have a "space blanket," one of those high-tech silvery-looking things they throw on marathon runners after the race. It's thin and light and should keep any of Mir's skilled denizens warm in case of heating system failures or unexpected misorientations away from the sun.

I have an old stationary bicycle that could serve double duty as gyroscope and power generator. The rider of that bike on board Mir, skimming over the atmosphere, could lay claim to having gotten nowhere faster than anyone in history.



MICHAEL CRAWFORD

Finally, I have a sleeve of Styrofoam cups. Combined with some PVC tubing and sweatsocks, both of which are probably already up there, these cups could no doubt be fashioned into a highly efficient carbon dioxide filter, based on what I remember from watching the movie *Apollo 13*.

All I ask in return for these goods is that the Russians change the name. Please. —*Steve Mir…sky*

In Brief, continued from page 28

Sauroposture
Computer modeling is turning a commonly held view of dinosaurs' feeding posture on its head. In the April 30 *Science,* Kent A. Stevens of the University of Oregon and J. Michael Parrish of Northern Illinois University reconstruct the neck articulation of two sauropod species, finding that the long-necked animals were much less flexible than had been widely believed. *Diplodocus* and *Apatosaurus* have been depicted in the past stretching swanlike necks to reach tall vegetation, a pose that raised the question of how their hearts pumped blood to their heads. It now seems that the animals held their necks nearly straight, angling them down to browse low-growing shrubs. —*J.N.*

Tuna Temperance
Good news for fishers and fish alike: the National Marine Fisheries Service issued a new plan in April to help rebuild Atlantic migratory fish stocks. Based on feedback from 27 public hearings and thousands of suggestions, the rules make bycatch reduction a top priority. Proposals to lower bycatch during swordfish, tuna and shark fishing include temporary closing of some areas, a change in fishing gear, increased education and limited access. For billfish, such as marlins and sailfish, the number caught will not be as important as meeting the minimum size limit. Sportfishers may catch only three yellowfin tuna per person a day. The rules are posted at www.nmfs.gov/sfa/hmspg.html —*C.R.*

Fishing rules

HERVÉ DONNEZAN *Photo Researchers, Inc.*

Fleshing Out the Family Tree
A hominid discovered in eastern Ethiopia is the latest candidate for a direct human ancestor and may represent the first butcher in the family. Scientists uncovered the 2.5-million-year-old fossils along an ancient lake margin, near a collection of cut and broken fossil animal bones of the same age. The proximity of the finds, described in two articles in the April 23 *Science*, may indicate that this primate was the first in our line to use kitchen tools. The species, named *Australopithecus garhi*, may fill a million-year gap in our history and combines surprising characteristics; thus the name *garhi*, which means "surprise" in the local Afar language. —*J.N.*

SA

CELL BIOLOGY

STEM CELLS COME OF AGE

Cells that can grow into a range of tissues are initiating a revolution in biology

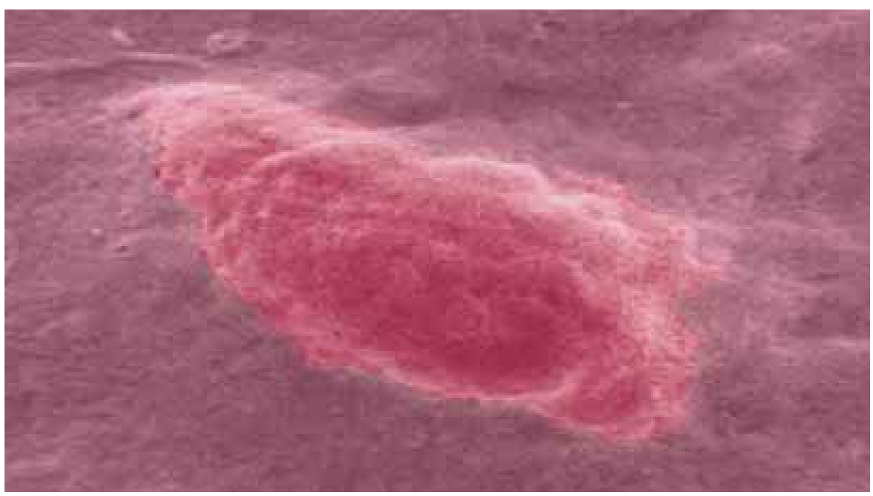
A flurry of startling discoveries in stem cell biology in past months has shattered preconceptions about how cell specialization is controlled in the body and has boosted the field to the top of scientific, political and commercial agendas. The excitement has raised hopes that the long-sought goal of being able to regenerate human tissues may be closer than had been thought.

Stem cells can replicate indefinitely and can also give rise to more specialized tissue cells when exposed to appropriate chemical cues. Embryonic stem cells, which are derived from the earliest developmental stages of an embryo and can spawn almost all types of cells in the body, hit the headlines last November, when James A. Thomson of the University of Wisconsin described his isolation of human versions. John D. Gearhart of Johns Hopkins University published at about the same time a report that he had isolated similar human cells, called embryonic germ cells, from the developing gonads of fetuses; he is now making progress in turning the cells into specific tissue types. Since then, more remarkable results have been disclosed, particularly with more specialized stem cells. Such cells lack the complete developmental flexibility of embryonic stem cells but can still give rise to a useful variety of cells.

The most impressive findings have come from animal work on neural stem cells, which are derived from the fetal brain and seem likely to exist in the adult brain, too. They grow readily in culture—unlike some other specialized stem cells—and can form all the types of cells normally found in the brain. Thus, they may be able to repair damage caused by Parkinson's disease and other neurological conditions. Evan Y. Snyder of Harvard Medical School and his colleagues have demonstrated that human neural stem cells respond appropriately to developmental cues when introduced into the brains of mice; they engraft, migrate and differentiate the way mouse cells do. Moreover, they can produce proteins in a recipient brain in response to genes that were artificially introduced into the donor cells.

Ronald D. G. McKay of the National Institute of Neurological Disorders and Stroke says it seems the same control systems that regulate specialization of cells in a fetus continue to operate in adults, making prospects for brain repair seem realistic. McKay's experiments indicate that neural stem cells placed in a rodent brain can form neurons and make synapses of types appropriate to their location, an indication they are functional.

Neural stem cells also seem to have a previously unsuspected developmental flexibility. Earlier this year Angelo L. Vescovi of the National Neurological Institute in Milan and his colleagues showed that neural stem cells can form blood if they are placed in bone marrow. Vescovi says that if other stem cell types can also modify their fates in this surprising way "you are looking at a reser-



GERON CORPORATION

HUMAN EMBRYONIC STEM CELL grows indefinitely in culture and seems able to spawn all the types of cells found in the body.

voir of cells in the adult that can regenerate all tissue types." Other clues that stem cells are flexible about their fates have emerged: Darwin Prockop of MCP Hahnemann University in Philadelphia has found that human bone marrow stromal cells, a type that had been thought to have nothing to do with nerve tissue, can form brain tissue when implanted into rat brains. And Bryon E. Petersen of the University of Pittsburgh and his associates demonstrated recently that stem cells from bone marrow can regenerate the liver.

Embryonic stem cells could be the most powerful ones of all, but only a small group of investigators is working with them, because at present only private funds are available. The National Institutes of Health has, in a controversial decision, announced that it will support scientists who want to work with established embryonic stem cell lines—but not investigators who want to establish the lines in the first place, because the process entails killing an embryo and so would contravene a congressional ban.

Although some 70 legislators have objected to the NIH decision, the agency is now drawing up guidelines to govern the work. They require that the cell lines must have been derived from freely donated spare embryos resulting from treatment of infertility, not from embryos created specifically for research. In late May the National Bioethics Advisory Commission was set to issue yet more liberal recommendations. It favors federal grants for scientists both to experiment with and to derive embryonic stem cells from abandoned embryos, a shift that would mean lifting the congressional ban on most embryo research.

Medical applications of embryonic stem cells will probably require cells that are genetically matched to the patient, so as to avoid rejection. Nuclear transfer, the central technology of cloning, could in principle provide matched cells, because a cloned embryo derived from a patient's cell sample could yield embryonic stem cells. Yet there could still be show-stoppers. It may turn out that embryonic stem cells descended from cloned embryos lack the full potential of those from natural embryos, for example. Indeed, many embryos resulting from nuclear transfer have defects, possibly because gene expression is abnormal in embryos that lack two genetic parents.

In an attempt to avoid the need to create embryos, Geron Corporation in Menlo Park, Calif., which has supported most of the work on embryonic stem cells to date, recently formed a $20-million alliance with the Roslin Institute near Edinburgh, home of Dolly the cloned sheep, and bought a spin-off company, Roslin Bio-Med. The objective is to study how the institute's cloning procedure succeeds in reprogramming adult cells so they can form multiple tissues. If successful, Geron might then be able to make stem cells of any type from adult tissue without the need for a donated egg and without the ethical complications of creating a cloned embryo.

Advanced Cell Technology in Worcester, Mass., is pursuing a different strategy: Michael D. West, the company's president, says he has preliminary indications that he can make human embryonic stem cells by fusing adult human cells with a cow's egg. But some scientists are skeptical, because embryos generally cannot develop if cells contain components from such different species. West, however, promises publication of dramatic results soon. The race toward the long-sought goal of human tissue regeneration may be entering its most exciting phase.

—Tim Beardsley in Washington, D.C.

PROFILE

Pinker and the Brain

Cognitive scientist Steven Pinker plumbs the evolutionary origins of language and behavior while keeping his detractors at bay

Steven Pinker does not shy away from fights. Over the years, he has taken on feminists, romanticists, psychoanalysts and fellow linguists, including the brilliant Noam Chomsky. But perhaps his most noted clash has been with Stephen Jay Gould, the paleobiologist. The intellectual feud between the two men, which also involves other leading evolutionary theorists, eventually landed on the front page of the *Boston Globe*.

So it is with some sense of trepidation that I meet Pinker, the 44-year-old professor of psychology and director of the Massachusetts Institute of Technology's Center for Cognitive Neuroscience. Entering his home, a beautifully remodeled Victorian house a short walk from Harvard University, I am expecting a churlish gadfly. But I am immediately disarmed by his soft-spoken and affable manner.

Pinker, who was born and raised in Montreal, recalls that a defining moment in his life occurred in the early 1970s, when he was in junior college (a transition between high school and university in Quebec). He happened to read "The Chomskyan Revolution," an article in the *New York Times Magazine* that described Chomsky's theories—in particular, his assertion that all languages have an underlying universal grammar. "It was the first time," Pinker remembers, "that I had heard of language being an innate ability."

The 1970s also marked the coming of another revolution, that of sociobiology, the study of how genes influence social behavior. Championed by biologist Edward O. Wilson, sociobiology attempted to link biology with the social sciences and humanities. Interestingly, Pinker turned his back on the emerging field, his early interest in the connection between biology and language notwithstanding. "I was probably opposed to sociobiology not for any serious reasons, but because everyone I knew was opposed to it," he recalls. "Especially after the Second World War, anything smacking of genes was suspect because of Hitler and eugenics."

So as an undergraduate at McGill University, Pinker opted for a more traditional route, studying cognitive science.

SAM OGDEN

"I found alluring the combination of psychology, computer science, artificial intelligence, the philosophy of mind, and linguistics," he says. In particular, he was impressed with the premise in cognitive science that information—memories, for instance—can be incarnated in matter or, more specifically, neural tissue. He was also attracted to the field's amenability to experimental verification. "Cognitive science," Pinker remarks, "gives you the framework and vocabulary to begin asking questions, and you can then form theories and go out and test them."

He began doing so at Harvard University, where he received a Ph.D. in psychology, and at M.I.T., where he has been since 1982. Pinker poked and prodded at Chomsky's theories, conducting experiments in the laboratory and at day care centers to determine exactly how children acquire language. He observed how toddlers from a very early age make certain errors, for example, in forming the past tenses of irregular verbs ("bringed" instead of "brought"). Such mistakes, Pinker asserted, occurred before the children had processed enough language to have inferred the appropriate rules from scratch. From that and other data, Pinker confirmed that children do indeed have an inborn facility for language, and he developed and tested detailed models for how that mechanism might work. But something was missing. If people have such an innate faculty, how did it get there?

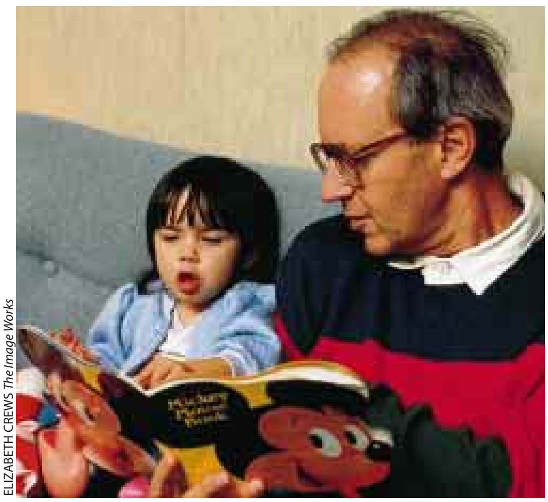
Then, during a sabbatical in the late 1980s, Pinker read Richard Dawkins's *The Selfish Gene* and about two dozen other books on evolutionary biology. "This was the logical next step," he recalls, "going from innate mechanisms such as those for acquiring language and asking, How did those mechanisms get there? And the answer is by the process of evolution." Pinker thus embraced evolutionary psychology, a field that (ironically for him) arose from many of the ideas of sociobiology.

If the human eye is an adaptation—that is, something functionally

***STANDING HIS GROUND:** Steven Pinker's embrace of evolutionary psychology has put him at odds with intellectual heavyweights such as Stephen Jay Gould and Noam Chomsky.*

effective that has evolved through natural selection—then so essentially is the human mind, evolutionary psychologists assert. Thus, various mental faculties, including that for language, and even human behavior might best be understood when viewed in this context, similar to the way in which technicians can reverse-engineer how a VCR works by first knowing what it does. Why, for example, do people fall in love with each other? Rather than a mere social construct, romantic love, evolutionary psychologists contend, evolved biologically as an insurance mechanism to guarantee that both parents stuck around to care for their offspring, thereby assuring continuity of their genes.

Pinker tells me this as we sit at his dining table, which has a full view of his immaculately furnished living room, where every piece of furniture and decorative touch seems to have its place. I suddenly understand how Pinker views the mind: not as a mysterious mess of inexplicable irrationalities but as a system where order and function rule.



ELIZABETH CREWS *The Image Works*

LANGUAGE ACQUISITION in toddlers is facilitated by an innate mechanism of the mind that arose through natural selection, Pinker asserts.

In 1994, in his first popular book, *The Language Instinct,* Pinker applied that tidy Darwinism to extend Chomsky's theories into adaptationist territory. Three years later he went much further with *How the Mind Works,* building on the work of anthropologist John Tooby, psychologist Leda Cosmides and others. The 660-page tome is an elegantly written tour de force that pulls together developments in cognitive science and evolutionary psychology, synthesizing them into a coherent and cohesive theory. The book did no less than explain a staggering range of phenomena—why people are disgusted at the thought of eating worms, why they have the proclivity for self-deception, why men buy pornography but women don't—all in evolutionary terms.

Pinker's persuasive prose aside, it is easy to see why evolutionary psychology elicits ire. Taken to a fanatic extreme, the field paints a bleak picture of people controlled by their genes. (Incidentally, the dark implications of biological determinism plagued Wilson and sociobiology in the 1970s.) Furthermore, biological differences between the sexes have an odd way of quickly becoming twisted into women-belong-back-in-the-kitchen arguments. And popular how-to books such as *Men Are from Mars, Women Are from Venus,* with their tenuous ties to evolutionary biology and their oversimplifications of the human mind, have not helped.

Pinker is quick to point out that "what is" must never be confused with "what should be." In fact, in *How the Mind Works* he bends over backward to make the distinction between science and morals. Nevertheless, "if you're a hostile reader," he notes, "I guess you read [into the book] what you want."

Pinker's battle with Gould might be characterized in the same way: each accuses the other of misrepresenting his views. In a nutshell, Gould asserts that Pinker and other "Darwin fundamentalists" have grossly overemphasized the role of natural selection at the expense of various other considerations—namely, everything from random genetic drifts to wayward meteors. Pinker acknowledges the importance of those factors but contends that a complex functional system such as the human mind must necessarily arise essentially from natural selection.

What irks many of Pinker's critics is the feeling that he and others have pushed their theories far beyond what the scientific data can support. According to biolinguist Lyle Jenkins of the Biolinguistics Institute in Cambridge, Mass., researchers have yet to understand all the individual development mechanisms (genetic, biochemical and so forth) that might have played a role in the biological evolution of the language faculty. "Unless you understand the whole problem, for example, the physical substrate that natural selection acts on, it's senseless to discuss whether language is an adaptation," he says. For these and other reasons, Chomsky, whose work laid the foundation for a biological basis to language, is himself reluctant to discuss whether language is an evolutionary adaptation. "I don't even understand what that means," he replies.

But others, including George C. Williams, one of the great evolutionary biologists of this century, assert that Pinker has indeed made the case for language being an adaptation. In fact, Williams says, "I recall getting annoyed at myself when reading *The Language Instinct* for not having thought of some of the things that Pinker came up with."

Weeks after meeting Pinker, as I sort through this debate, I become troubled by other issues. For one thing, why hasn't evolutionary psychology, an arguably powerful paradigm for explaining normal behavior, led to any treatments for mental illnesses such as schizophrenia and manic-depressive disorder? Pinker explains that if such illnesses prove to be physiological (perhaps caused by pathogens), they may be untreatable by psychological intervention, evolutionary or otherwise. For milder disorders, such as depression and phobias, Pinker says that clinical psychologists and psychotherapists are beginning to investigate evolution-based approaches.

Indeed, Pinker concedes that evolutionary psychology's work is hardly done, even for exploring everyday phenomena. Why, for example, do people derive such pleasure in listening to music? "A lot of times there'll be these embarrassing facts that you tuck away, thinking there's got to be an answer to them if only you had the time to look into it," he says. "But what you don't realize is that sometimes those facts are the ones that hold the key to a mystery, and so you've got to take those facts seriously because they change everything."

How such inconvenient facts and unsolved mysteries might muck up Pinker's neat landscape of the mind is unknown. For now, though, evolutionary psychology provides a plausible, if incomplete, approach for understanding the mind, and Pinker has certainly been instrumental in publicizing this paradigm. In the introduction to *How the Mind Works,* he writes, "Every idea in the book may turn out to be wrong, but that would be progress, because our old ideas were too vapid to be wrong."—*Alden M. Hayashi*

MOLECULAR BIOLOGY

PARSING CELLS

Proteomics is an attempt to devise industrial-scale techniques to map the identity and activities of all the proteins in a cell

Biological cells are not genetic reductionists. The readouts from a gene-sequencing machine do not tell you much about the ultimate structure and function of the cellular proteins made by the genes. After a protein comes off the gene-to-amino-acid assembly line, it is altered as it assumes its place as a cog in the cellular machinery. Carbohydrates, phosphates, sulfates and other residues are pasted onto it. Enzymes may chop the amino acid chain into smaller pieces. A single gene may thus code for several different proteins.

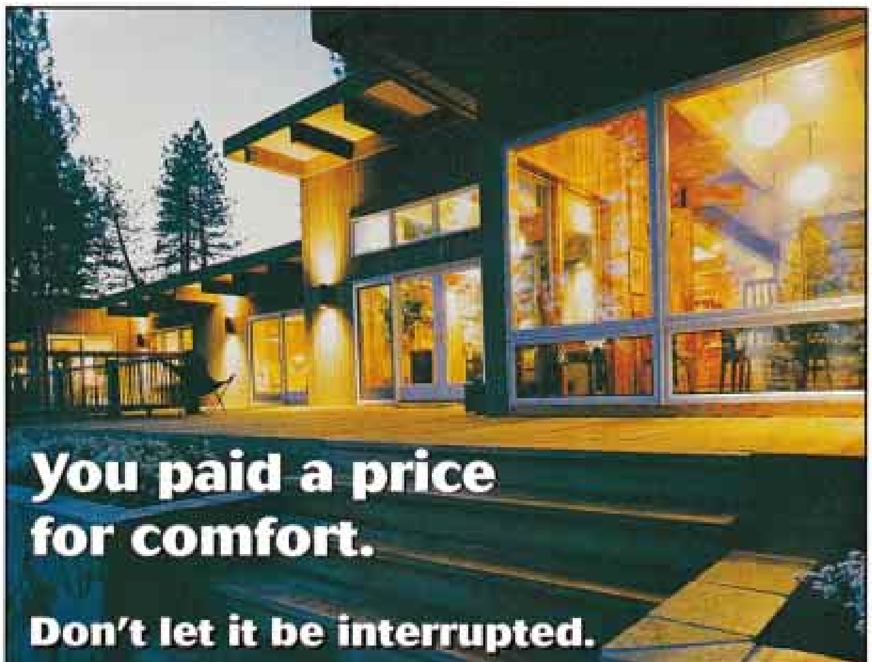
A new biological subdiscipline called proteomics tries to circumvent the information gap between DNA and its end products. Proteomics envisions deducing the structure and interactions of all the proteins in a given cell. Comparing proteomic maps of healthy and diseased cells may allow researchers to understand changes in cell signaling and metabolic pathways better. And pharmaceutical companies might devise diagnostic tests and identify new drug targets.

Molecular biologists have tried to parse a cell's protein makeup for decades. "There's nothing new about identifying proteins in a cell," notes Marvin Cassman, director of the National Institute of General Medical Sciences (NIGMS). "What's different here is to do things in a global sense rather than looking at one protein here and there." Similar in concept to genomics, which seeks to identify all genes, the field's success will depend on the ability to develop techniques that can rapidly identify the type, amount and activities of the thousands of proteins in a cell.

CIPHERGEN BIOSYSTEMS

***PROTEIN CHIP** is inserted into a mass spectrometer to read the amino acid sequence of proteins contained in each circular well.*

A slew of new biotechnology companies have started marketing technologies and services for mining protein information en masse. Oxford Glycosciences (OGS) in Abingdon, England, has automated a time-worn technique, two-



dimensional gel electrophoresis. In the OGS process, an electric current applied to a sample on a polymer gel separates the proteins, first by their unique electric charge characteristics and then by size. A dye attaches to each separated protein arrayed across the gel. Then a digital imaging device automatically detects protein levels by how much the dye fluoresces. Each of the 5,000 to 6,000 proteins that may be assayed in a sample in the course of a few days is channeled through a mass spectrometer that determines its amino acid sequence. The identity of the protein can be determined by comparing the amino acid sequence with information contained in numerous gene and protein databases. One imaged array of proteins can be contrasted with another to find proteins specific to a disease.

Proteomics aspires to know more than just the identity of a set of proteins. Small Molecule Therapeutics, based in Monmouth Junction, N.J., has developed one approach to understanding what a protein actually does. Its technique first finds two proteins that interact with each other and then creates fragments of one of the proteins. Some of the fragments may block any further interactions with the intact protein. Researchers assess how a cell's biological functions are altered by this inhibition. The company has used the technique to pinpoint inhibitors of the signaling protein RAS, which can trigger cancer.

The suite of techniques under development for proteomics have yet to become as routine as gene sequencing. Doubts persist, for instance, about how ably two-dimensional gel electrophoresis can separate all the proteins in a cell. Researchers are working on linking mass spectrometry with newer separation methods, which could improve both speed and sensitivity of protein identification. Companies such as Ciphergen Biosystems, based in Palo Alto, Calif., labor on the protein equivalent of gene chips. One of these rapid assays consists of an array of up to 96 millimeter-square metal or plastic wells, each filled with an antibody, a receptor or a synthetic molecule that traps a protein. The proteins can then be desorbed and identified with a mass spectrometer.

The possibility of a Human Proteomics Initiative intrigues some scientists. But the exact focus of a program remains unclear: Should it try to determine the levels of proteins in all the 250 or so human cell types? Or should it try to elicit the billions of possible protein-to-protein interactions? "It would need to have well-defined goals and milestones," says Francis S. Collins, who oversees the Human Genome Project at the National Institutes of Health. "Again, that will be much more difficult than for nucleic acids. How do you decide when you're done?"

The NIGMS, for one, has taken a step toward a large-scale proteomics effort by initiating a program that would determine whether crystallographic and nuclear magnetic resonance techniques could become highly automated. The project will attempt to ascertain the three-dimensional structure of 10,000 proteins in the next five to 10 years, a rapid-fire pace for this painstakingly slow process.

Proteomics is only the beginning. Other biological endeavors have been rear-ended by a new suffix. Buzzwords ranging from metabolomics to transcriptomics to phenomics have proliferated as entire areas of the life sciences are analyzed. Perhaps someday all things biological will be classified and jammed into an enormous database—leading to some hypothetical metadiscipline called biomics. *—Gary Stix*

ROCKET SCIENCE

LOTS IN SPACE

With a new rocket, Arianespace hopes to stay on top of the commercial launch business

Nothing shatters the serenity of the rain forest quite like a rocket launch. In French Guiana, local fishermen working their ancient profession in their equally age-old canoes off the coast of Kourou are jarred into the 20th century every three weeks as another Ariane 4 rocket blasts through the sky to hoist a satellite toward its appointed orbital rounds.

Tropical backwater though it may be, Kourou is now the global center for geosynchronous satellite launches. "For the moment we have more than 55 percent of the market of the world," says Jean-Yves Trebaol, Ariane range operations director. "Our hope for the future is to keep with this rate and have 30 percent of the market for constellations [of nongeosynchronous satellites]." Yet whether Arianespace can achieve that goal depends on whether its newest rocket proves to be reliable after only one successful test flight. Moreover, the competition is growing stronger in this literally volatile field, as other firms enter the launch business.

The first commercial space transportation company, Arianespace took advantage of a missile gap that opened up when the National Aeronautics and Space Administration turned away from expendable launch vehicles, hoping to amortize its ambitious space shuttle program through commercial applications: the shuttle was to be the main vehicle for virtually all payloads, commercial and government. This policy came crashing down with *Challenger* in 1986. In 1990 NASA announced that it would no longer accept commercial payloads unless they "required the unique capabilities" of the shuttle crew.

In any case, customers found they

ALAIN NOGUES *Sygma;* ARIANESPACE *(inset)*

***EXPLOSION AFTER LIFTOFF** of the first Ariane 5 rocket was followed 17 months later with a smooth launch* (inset).

could launch heavier payloads more cheaply from equatorial Kourou than they could from Cape Canaveral, thanks to the extra shove provided by the earth's rotation there. Today Arianespace's Ariane 4 is perhaps the most reliable launch vehicle: only eight failures have marred 117 launches since 1988. Although Arianespace is a European company, American firms commission more than half the launches.

And now Arianespace has begun phasing out the Ariane 4 over the next four years in favor of a completely new launch vehicle, the heavy-lift Ariane 5, which can carry almost double the payload. Ariane 5, though, has had a shaky debut. The first one exploded soon after its 1996 liftoff because of faulty commands from software recycled from the Ariane 4. The second Ariane 5, launched in 1997, began rolling unexpectedly after booster separation and placed its satellite payload in an unusable orbit. Still, the company has labeled that launch a success. The third launch, in late 1998, carried a mock commercial satellite and a reentry capsule that could one day be used for manned flight. This time, everything went according to plan—and the capsule splashed down precisely on target.

"That means we now know how to insert something into orbit and have it down whenever and wherever we want," says Arianespace spokesperson Claude Sanchez. "It means that we are mastering the whole process of space transportation." Not long after that flight, Arianespace declared the Ariane 5 fully operational. "We learn more from our failures than from our successes," Sanchez explains.

The pressure for the Ariane 5 to succeed has grown intense: the company has a gleaming new vehicle infrastructure in Kourou that needs to be paid for, three commercial Ariane 5 launches scheduled for the last half of this year (the first of which has been postponed), and a two-and-a-half-year launch backlog of 40 satellites and one constellation worth nearly $4 billion.

Meanwhile Arianespace has growing competition. Trebaol rattles off the players: along with Lockheed-Martin's heavy-lift Atlas booster and Boeing's Delta (both of which have recently suffered spectacular failures), Russia's Proton and China's Long March are now available for commercial launch. The newest kid on the block: Sea Launch, a consortium that includes Boeing, Russia's RSC-Energia and Ukraine's KB Yuzhnoye/PO Yuzhmash, which builds the Zenit rocket. As the name implies, the Sea Launch booster begins its journey from the middle of the Pacific Ocean, from a converted oil-drilling platform on the equator. Range safety isn't an issue out there, and satellites can achieve a geosynchronous orbit more quickly and cheaply than from Kourou or the Cape. A supply ship, the *Commander*, can carry three Zenits at sea; the rockets are then hoisted onto the platform by a crane. For the debut launch, however, the platform made its 14-day journey from Long Beach, Calif., to the equator with the Zenit rocket already in place.

Although the Zenit has had several launchpad failures, the first Sea Launch attempt this past March was a success—except that it carried a satellite mockup. The Zenit's checkered past made paying customers nervous. Still, Sea Launch says it has orders for 15 launches and has declared its system fully operational. "We can shoot up to 11,000 pounds, which is right up between the Ariane 4 and 5," says Sea Launch spokesperson Terrance L. Scott.

Right now Arianespace is betting the works on the Ariane 5: the company has 13 on order and intends to buy 50 more. By the time the last Ariane 4 leaves the ground in 2003, Kourou will be able to launch 10 to 12 Ariane 5s per year—or more, if the market demands. "Satellites are getting bigger. In 2005 the average satellite will weigh five to six tons," Trebaol predicts. The implication: the Ariane 5 should be able to boost two of them with ease—if it can continue the tradition of reliability wrought by the Ariane 4.

—Phil Scott in Kourou, French Guiana

PHIL SCOTT, based in New York City, described flying mechanical insects in the April issue.

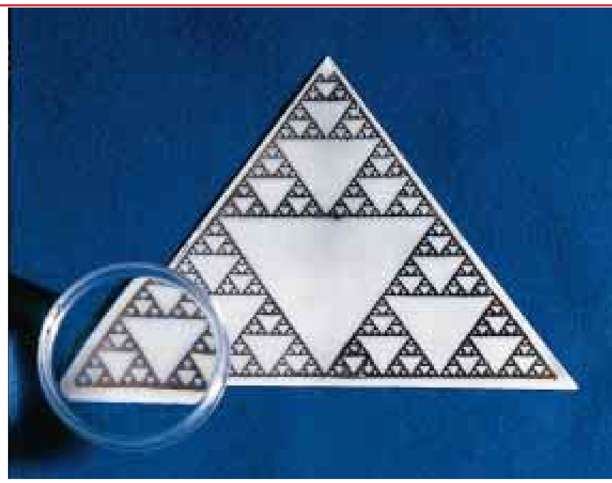
WIRELESS COMMUNICATIONS

Practical Fractals

Fractals have become one of the unifying principles of science, but apart from computer graphics, technological applications of these geometric forms have been slow in coming. Over the past decade, however, researchers have begun applying fractals to a notoriously tricky subject: antenna design.

Antennas seem simple enough, but the theory behind them, based on Maxwell's equations of electromagnetism, is almost impenetrable. As a result, antenna engineers are reduced to trial and error—mostly the latter. Even the highest-tech receivers often depend on a scraggly wire no better than what Guglielmo Marconi used in the first radio a century ago.

Fractals help in two ways. First, they can improve the performance of antenna arrays. Many antennas that look like a single unit, including most radar antennas, are actually arrays of up to thousands of small antennas. Traditionally, the individual antennas are either randomly scattered or regularly spaced. But Dwight Jaggard of the University of Pennsylvania, Douglas Werner of Pennsylvania State University and others have discovered that a fractal arrangement can combine the robustness of a random array and the efficiency of a regular array—with a quarter of the number of elements. "Fractals bridge the gap," Jaggard says. "They have short-range disorder and long-range order."



FRACTAL TRIANGLE can act as a miniaturized antenna.

Second, even isolated antennas benefit from having a fractal shape. Nathan Cohen, a radio astronomer at Boston University, has experimented with wires bent into fractals known as Koch curves or fashioned into so-called Sierpinski triangles (*above*). Not only can crinkling an antenna pack the same length into a sixth of the area, but the jagged shape also generates electrical capacitance and inductance, thereby eliminating the need for external components to tune the antenna or broaden the range of frequencies to which it responds.

HIDDEN INSIDE a cordless phone, a square fractal antenna (center board) *replaces the usual rubbery stalk.*

Cohen, who founded Fractal Antenna Systems four years ago, is now working with T&M Antennas, which makes cellular phone antennas for Motorola. T&M engineer John Chenoweth says that the fractal antennas are 25 percent more efficient than the rubbery "stubby" found on most phones. In addition, they are cheaper to manufacture, operate on multiple bands—allowing, for example, a Global Positioning System receiver to be built into the phone—and can be tucked inside the phone body (*left*).

Just why these fractal antennas work so well was answered in part in the March issue of the journal *Fractals*. Cohen and his colleague Robert Hohlfeld proved mathematically that for an antenna to work equally well at all frequencies, it must satisfy two criteria. It must be symmetrical about a point. And it must be self-similar, having the same basic appearance at every scale—that is, it has to be fractal.

—George Musser

PHOTOGRAPHS BY ANDY RYAN; ANTENNAS COURTESY OF FRACTAL ANTENNA SYSTEMS

OPTICS

HOLEY MAGIC

A "spooky" optical phenomenon may yield brighter laptops and faster microchips

To less learned eyes, it might have seemed magical. Even physical chemist Thomas Ebbesen felt a "spooky" thrill when, 10 years ago, he raised a gold-plated glass microscope slide up to his eyes and saw not just his reflection in it but also the other side of the room through it. This was not the way that gold and light were supposed to behave.

Ebbesen, who was then working at NEC Research in Japan and is now affiliated with the company's laboratories in Princeton, N.J., did expect to see a little light coming through the gold film, because he had used an ion beam to riddle the metal layer with 100 million microscopic holes. But those holes were so minuscule—each just a few hundred nanometers in diameter, less than half the wavelength of visible light—that basic physics predicted that any view through them would be dim and indistinct. "Like frosted glass," says Tineke Thio, Ebbesen's collaborator at NEC.

But in fact, "I could see not just light but color, outlines. It was like wearing sunglasses," Ebbesen recalls. At the time, he could not have known what a technological opportunity the phenomenon offered. What he did know, Ebbesen says, was that "this was a serious puzzle."

With investigation, the mystery only deepened. Further experiments confirmed that up to 50 percent of the light hitting certain perforated films passed through them even though holes pierced only 20 percent of their area. This is rather like seeing a window that lets in as much light as an open door twice its size. The effect was oddly finicky about colors: at some wavelengths light was transmitted 1,000 times more intensely than conventional theory predicted. Yet some other colors weren't boosted at all.

As Ebbesen's group tested myriad permutations of materials and hole arrangements, they discovered to their great surprise that the phenomenon worked with any metal film, not just gold. And it worked on lots of transparent substrates, not just glass. It worked as well with seven holes as with several million.

For nearly 10 years, Ebbesen struggled with the problem, waiting, in the closed-mouth habit of corporate researchers, to make his findings public until he could explain and control (and patent) the phenomenon. "Until just a few years ago, we were extremely confused," Ebbesen says.

But in March, at a meeting of the American Physical Society in Atlanta, Thio reported that they now have a working theory and have demonstrated ways to control the color and brightness of light passing through such perforated films. Ebbesen credits Peter A. Wolff of the Massachusetts Institute of Technology with the theoretical breakthrough, the idea that roving packs of electrons called plasmons somehow shepherd light into the holes.

"If you think of a sea of electrons floating on the surface of a metal, then the plasmons are like waves sloshing around in that sea," Ebbesen explains. "Making these holes is like sinking pilings into the water: it changes the patterns of the waves." The shifting plasmons generate swirling electric and magnetic fields that transmute the perforated gold surface from dull mirror into something more akin to a sieve, Thio elaborates. "It's like a photon strainer: even light that falls outside the holes gets funneled through."

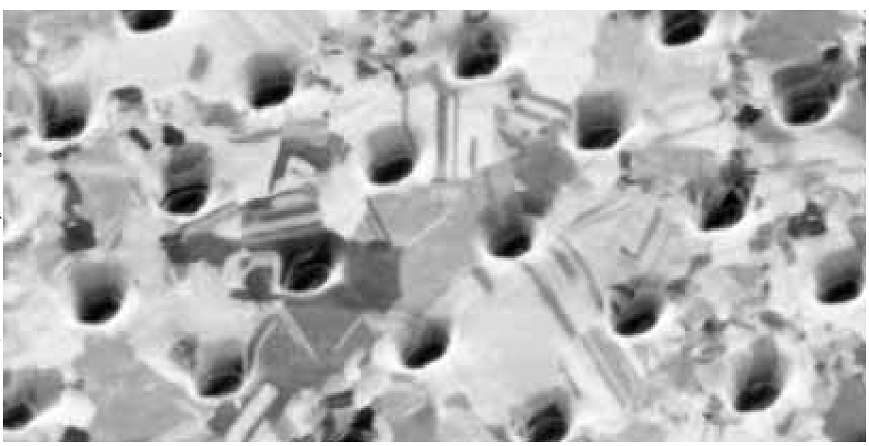
Optical sieves may eventually find many uses; NEC is focusing on two potentially lucrative ones. The first is stronger, brighter microcircuitry masks that could be laid directly on top of silicon wafers to etch much more detailed patterns into them than current photolithography machines can. Such an advance could extend the life of existing microchip plants, saving chipmakers billions of dollars.

The second application, in flat-panel displays, would exploit the ability of optical sieves to change which colors they let pass and which they block. The NEC group has found two ways to do this. One method is to vary the spacing of the holes; another is to adjust the angle at which light hits them, perhaps by using a layer of liquid crystal sandwiched next to the metal film.

In Atlanta, Thio reported some success with both techniques. One of her prototype devices can change a mixture of two laser beams transmitted through the sieve from red to yellow to green without using filters or polarizers, as current liquid-crystal displays (LCDs) do. In principle, optical sieves could be paired with light-emitting diodes or television-style phosphors to make displays that shine six times brighter than current flat-panel monitors—or that drain batteries much more slowly.

In practice, engineers will have to find cheap ways to make large nanoperforated sheets if they are to compete with LCDs. Douglas H. Adamson of Princeton University presented a novel method at the March conference that may serve. His team found a pair of polymers that, when mixed and coated onto a silicon wafer, react chemically so that one of the polymers self-assembles into a checkerboard pattern of spheres, each just a few hundred nanometers in diameter. By dissolving out the spheres and then etching through the remaining polymer, they can quickly create relatively large pieces of holey metal—and at a small fraction of the cost of drilling holes one at a time, as Ebbesen does. That may be just the magic trick needed to make optical sieves practical.

—W. Wayt Gibbs in Atlanta



HENRI J. LEZEC ISIS, Louis Pasteur University, Strasbourg

OPTICAL SIEVE, made by a beam of charged atoms that drilled 150-nanometer-wide holes in a silver film, lets up to 1,000 times as much light pass through its holes as physicists had thought possible.

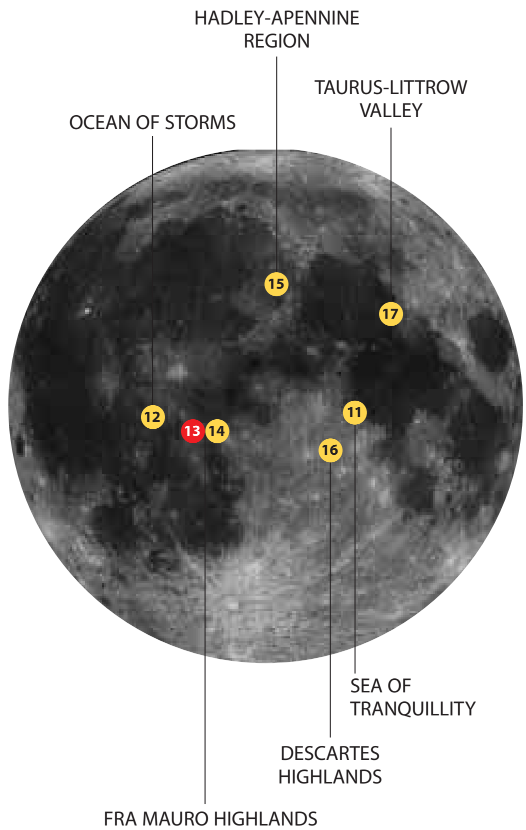
Looking Back at Apollo 11

On the 30th anniversary of the first manned lunar landing, digital reproductions of the Apollo photographs show the moon as the astronauts saw it

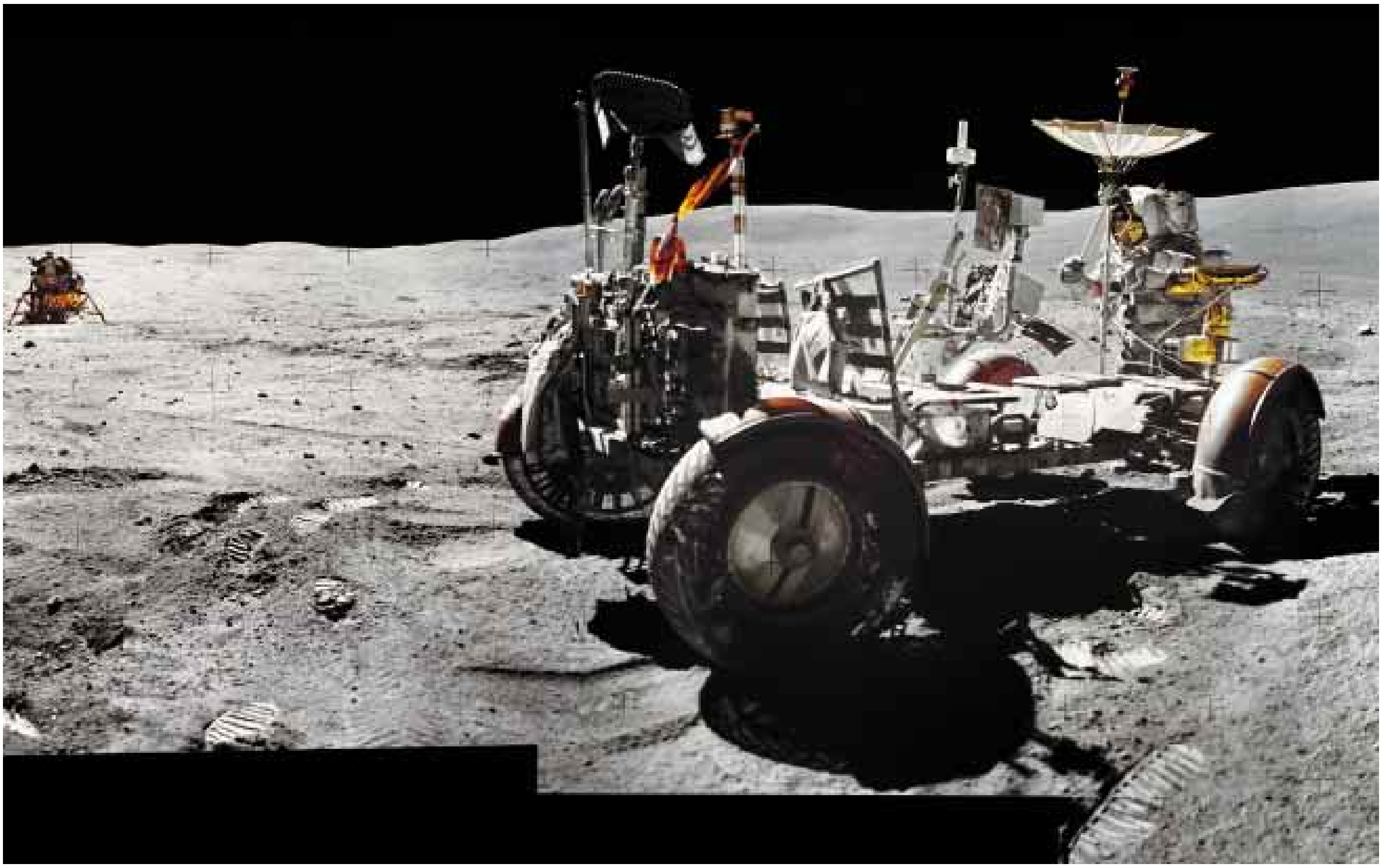
On July 20, 1969, on a vast basaltic plain known as the Sea of Tranquillity, astronauts Neil A. Armstrong and Edwin "Buzz" Aldrin, Jr., became the first men to walk on the moon. Thirty years later scientists are still poring over the evidence gathered by Armstrong, Aldrin and the 10 Apollo astronauts who followed them to the lunar surface over the next three years. During the six successful manned missions to the moon, the dozen astronauts collected a total of 380 kilograms (838 pounds) of lunar rock. But just as impressive as the geologic samples was the photographic evidence: 32,000 still pictures, including thousands of shots taken by the astronauts with Hasselblad cameras mounted on the fronts of their space suits.

The film returned to Earth was so precious that technicians at the National Aeronautics and Space Administration duplicated the images just once before putting the film in cold storage. The master duplicates were then used to make copies for newspapers, magazines and museum exhibitions. Until recently, most of the Apollo pictures seen by the public were actually fourth- or fifth-generation copies, with little of the clarity of the original images. But in a new book entitled *Full Moon* (Alfred A. Knopf, 1999, $50), artist and photographer Michael Light presents a selection of 129 Apollo images that have been digitally scanned from the master duplicates. The sharp, striking photographs capture moments from nearly all the Apollo missions, showing every stage of the journey to the moon.

Three of those photographs are featured on the following pages. Accompanying the images is an excerpt from "The Farthest Place," an essay in *Full Moon* written by Apollo historian Andrew Chaikin. —*The Editors*



LANDING SITES of the Apollo missions are shown on a composite image of the moon's near side. The lunar modules of Apollo 11 *and* Apollo 12 *landed on basaltic plains, whereas the subsequent Apollo missions explored more rugged areas.* Apollo 13 *was scheduled to visit the Fra Mauro Highlands, but an oxygen-tank explosion forced the spacecraft to return to Earth. The Fra Mauro site was then reassigned to* Apollo 14.



LUNAR ROVER is shown with Apollo 16 *commander John W. Young on the moon's Descartes Highlands. The lunar module* Orion *is in the background. The battery-powered rovers, used in the last three Apollo missions, could carry two astronauts and all their equipment for miles across the lunar surface.*

SPLIT ROCK, a massive lunar boulder broken into five pieces, was studied intensively by the astronauts in the Apollo 17 *mission to the Taurus-Littrow Valley. To the right of the lunar rover, mission commander Eugene A. Cernan uses a gravimeter to measure variations in the moon's gravitational field.*

Through the lunar module's two triangular windows, the moon seemed inviting, but it was more hostile than any place previously visited by human beings. On this airless world, an unprotected man would be exposed to the vacuum of space, and would perish in seconds. Then there were the hazards of deadly solar radiation, cosmic rays and micrometeorites. Before they could emerge, then, the astronauts had to seal themselves inside pressurized space suits. A special backpack provided oxygen, radio communications and cooling water; the last was circulated through tubes in a special set of long underwear to keep the moonwalker cool despite his exertions. Lunar boots featured treads to give firm footing in the dust, and a lunar visor featured a reflective gold-plated faceplate to screen out the sun's glare. Fully suited, each man was a self-contained mobile spacecraft. Inside his pressurized suit, he heard only the whoosh of oxygen flowing past his face, the steady whir of pumps circulating cooling water from the backpack, and the voice of Mission Control in his earphones....

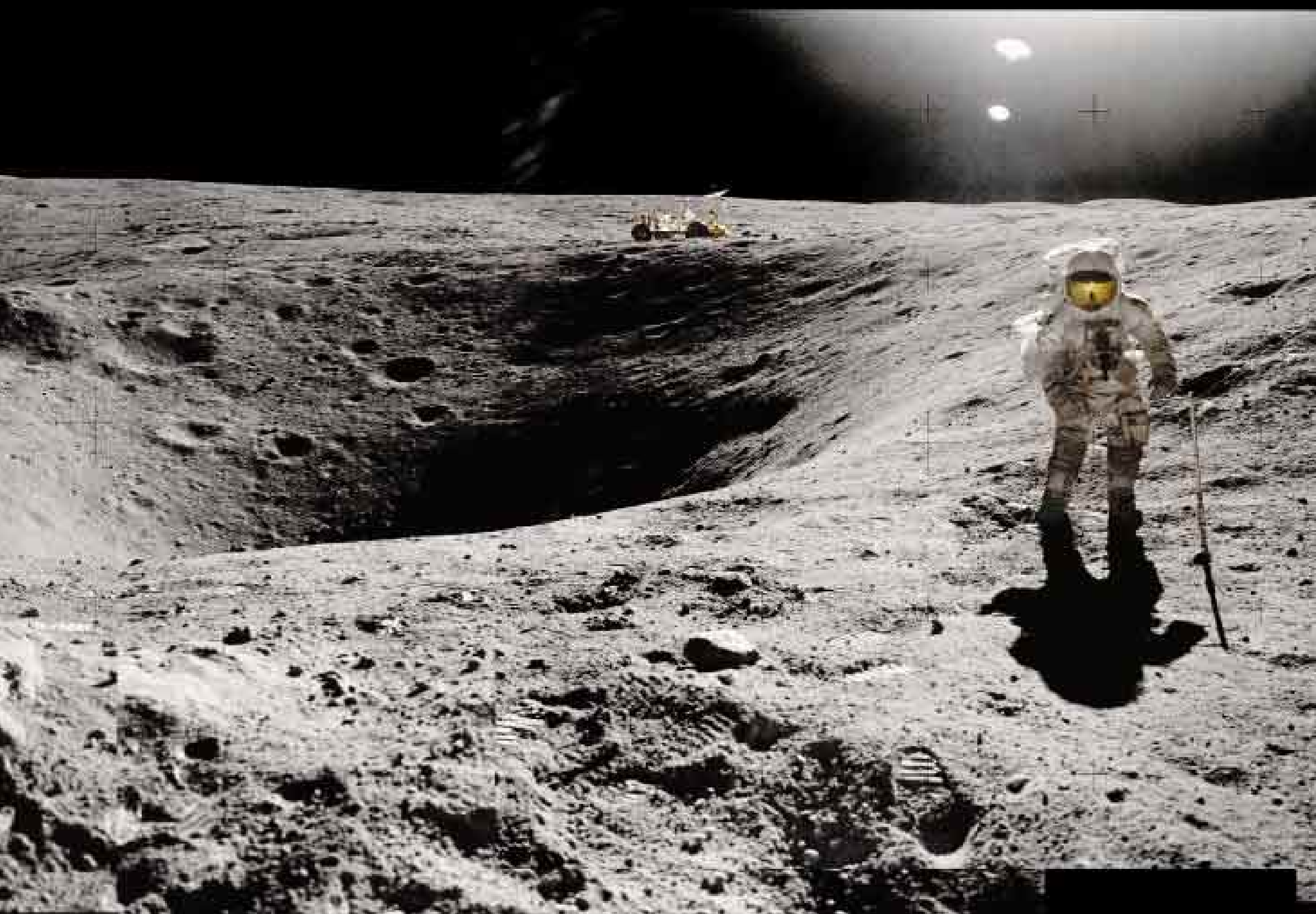
If astronauts suffered discomfort or even pain, it was eclipsed by the majesties of something far greater: their encounter with the moon. Indeed, the simple fact of being there was enough to create a high that lasted throughout the visit. What they saw through the visors of their space helmets was often literally incredible to them. Apollo 17's Eugene Cernan recalled, "You just stand out there and say, I don't believe what I'm looking at!"

Such comments can often serve to whet the listener's appetite for more expansive descriptions, but the astronauts—who were chosen for their skills as pilots, not poets—have had a tough time delivering. Still, one surprising word—beauty—threads through their transmissions from the moon and their post-flight reflections. In the first minutes of the first moonwalk, Apollo 11's Neil Armstrong—usually the essence of calm reserve—let excitement invade his voice as he radioed, "It has a stark beauty all its own.... It's very pretty out here." The eleven men who followed him to the lunar surface spoke their own variations on the theme. John Young described Apollo 16's Descartes Highlands as "one of the most dazzlingly beautiful places ever visited by a human being." And moments before taking his first lunar footsteps, Buzz Aldrin gazed out at the Sea of Tranquillity and said simply: "Magnificent desolation." —*Andrew Chaikin*

From *Full Moon* (Alfred A. Knopf, 1999)

APOLLO 11
July 16–24, 1969
Crew: Neil A. Armstrong
Michael Collins
Edwin E. Aldrin, Jr.

APOLLO 12
November 14–24, 1969
Crew: Charles Conrad, Jr.
Richard F. Gordon, Jr.
Alan L. Bean



APOLLO 13
April 11–17, 1970
Crew: James A. Lovell, Jr.
John L. Swigert, Jr.
Fred W. Haise, Jr.

APOLLO 14
January 31–February 9, 1971
Crew: Alan B. Shepard, Jr.
Stuart A. Roosa
Edgar D. Mitchell

APOLLO 15
July 26–August 7, 1971
Crew: David R. Scott
Alfred M. Worden
James B. Irwin

CRATERED LANDSCAPE of the Descartes Highlands is c
Apollo 16 astronaut Charles M. Duke, Jr., at two differe
into the lunar soil to extract a core sample (*left*); then
nar rover is in the background, parked near the rim
Young shot this sequence of photographs to provide a

APOLLO 16
April 16–27, 1972
Crew: John W. Young
Thomas K. Mattingly II
Charles M. Duke, Jr.

APOLLO 17
December 7–19, 1972
Crew: Eugene A. Cernan
Ronald E. Evans
Harrison H. Schmitt

TIMELINE BY EDWARD BELL *Scientific American*

captured in this composite image that shows
nt points in his moonwalk. First, Duke bores
he moves on to his next task (*above*). The lu-
of a crater. *Apollo 16* commander John W.
panoramic view of the rock-sampling site.

SCIENTIFIC AMERICAN

On-Line U.

The past few years have seen a race on-line by higher education. The notion of reaching students who can't fit into the standard residential degree programs has gotten schools everywhere putting everything from individual courses to entire degree programs in cyberspace. The institutions include the traditional universities, such as the University of California at Los Angeles, and distance-learning specialists, such as the University of Phoenix, along with cyber start-ups such as the Western Governors University project and the California Virtual University. Plenty of opportunity exists in remote education: Britain's 30-year-old Open University, the worldwide pioneer in distance learning, had by 1998 awarded more than 200,000 bachelor's degrees since the school's inception in 1969. Management guru Peter F. Drucker has predicted the death of the traditional residential higher education within 30 years.

Now two reports released in April question whether on-line learning can do what's been claimed for it. The first, "The Virtual University and Educational Opportunity," was published by the College Board in Princeton, N.J., and warns that the Internet could become an engine of inequality. Poor kids, the report argues, are less likely to be familiar with the technology or have access to the equipment. Three quarters of households with incomes greater than $75,000 have computers, as opposed to one third with incomes between $25,000 and $35,000 and one sixth of those with incomes less than $15,000.

Other research has backed up these conclusions. Donna Hoffman and Tom Novak, electronic commerce specialists at Vanderbilt University, studied race and its impact on Internet access. They concluded that a racial digital divide exists even after other variables such as income, class and education were accounted for, and they note that access is correlated strongly with income and education. A National Science Foundation–funded study carried out in Pittsburgh discovered that without special care, access gravitated toward the already advantaged schools and students.

The second report, "What's the Difference?", is an overview of research into the efficacy of different types of distance-learning technology. Carried out by the Institute for Higher Education Policy (IHEP) on behalf of the American Federation of Teachers and the National Education Association, it concludes that there is no proof that the "learning outcome" is on a par with traditional classroom teaching. The report criticizes the research efforts for, among other things, studying individual courses instead of overall programs; ignoring the dropout rate (typically higher in on-line courses) in assessing overall success; failing to control for extraneous variables; and failing to show the validity of the instruments used to measure those learning outcomes. In addition, it complains that the research does not adequately assess the effectiveness of digital libraries as compared with physical ones or consider how different learning styles relate to specific technologies.


DAVID SUTER

In other words: we're racing headlong into a new set of educational techniques we don't really understand. Given that an ever increasing percentage of the U.S. economy depends on knowledge workers and that those workers need to be highly educated and skilled, this move to cyber learning could be really stupid.

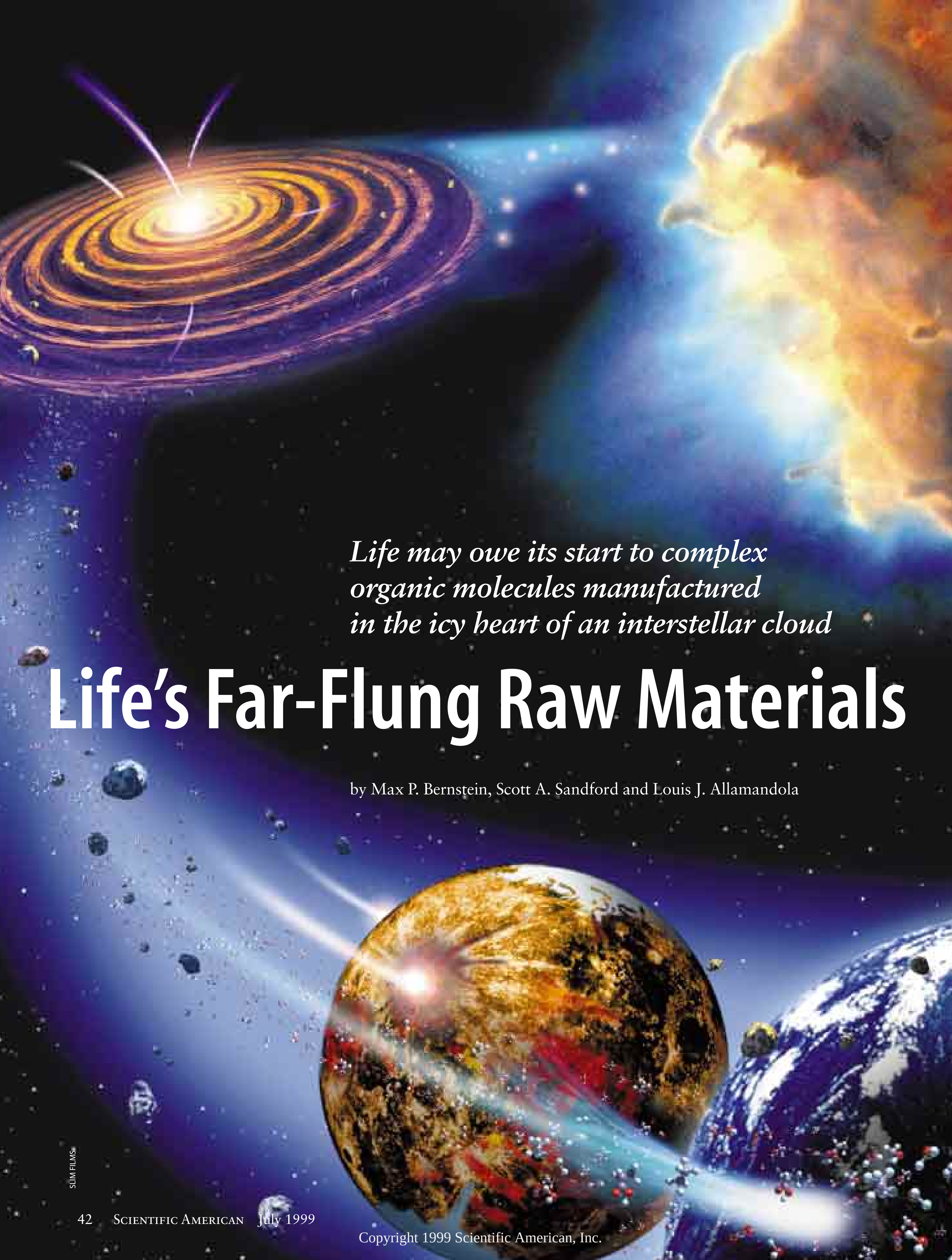
And yet the trend has not received much critical attention. One exception is an October 1997 essay called "Digital Diploma Mills," by historian David F. Noble of York University in Toronto. In it, Noble connects the soaring cost of a university education with what he claims is the commercialization of academia since the mid-1970s, when industrial partnerships and other commercial exploitation of university-based discoveries and research became common. (Some of these efforts are impressively organized: the Massachusetts Institute of Technology, for example, maintains its own office solely to assist students and staff in filing for and getting patents.) Noble believes moving courses on-line is part of a larger drive to "commodify" university education and de-skill the labor force—that is, college professors.

There are, of course, many other issues, such as accreditation and, as the IHEP report stated many times, access to libraries. An important one as well: What happens to student interaction, a reason people go to universities in the first place? Nowhere outside a university do you rub shoulders with such a variety of people with so many different interests. Reproducing the student experience on-line is very much harder than creating courseware. The University of Oxford, which last year announced it was preparing Web-based courses for lifelong learning, wants to replicate its famed personal tutorial system on-line.

Bob McIntyre, the program's manager, commented that many universities, struggling with overburdened staff, see the Internet as a way to make themselves more economical, a trend he doesn't think is healthy in the long-term. But because computer vendors look at higher education as a potentially huge revenue source, he is most worried that there would ultimately be only five universities worldwide—and they would be Microsoft, Disney... you get the picture.

Distance learning does have its place: the only way for people to satisfy the needs of most professions that demand constant updating of skills is either through very short courses or through distance learning—unless we want everyone to take two years off work to go to school every five or 10 years. Even so, the fact is that like it or not, most of the time learning is something that happens between people. It is not broadcasting, however much it feels like it when your professor's lecture heads into the second hour. —*Wendy M. Grossman*

WENDY M. GROSSMAN, based in London, described the issue of downloading music from the Internet in the May issue.



SLIM FILMS

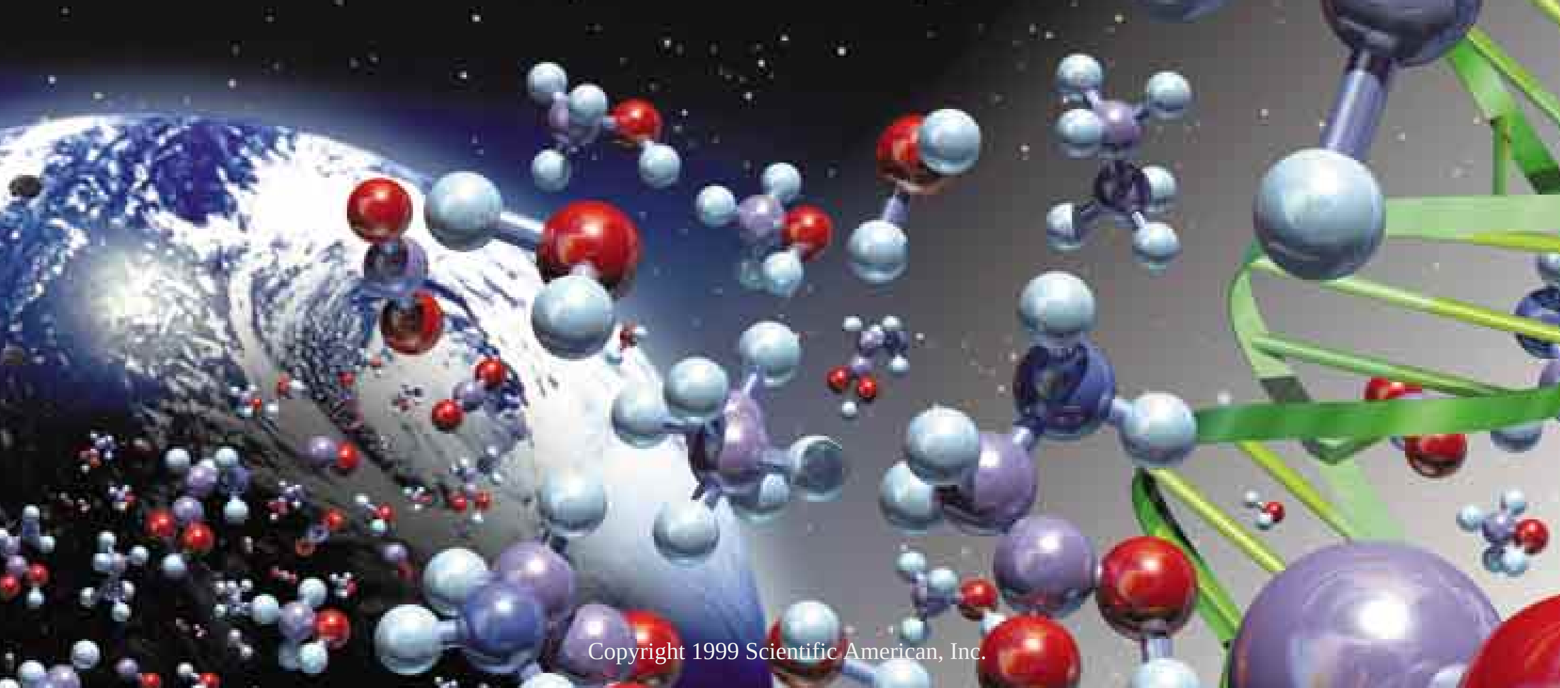
Life may owe its start to complex organic molecules manufactured in the icy heart of an interstellar cloud

Life's Far-Flung Raw Materials

by Max P. Bernstein, Scott A. Sandford and Louis J. Allamandola

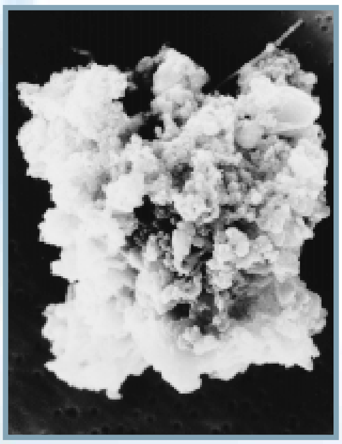
For centuries, comets have imprinted disaster on the human mind. By 400 B.C. Chinese astronomers had sketched 29 varieties of comets, many foretelling calamity. Aristotle's assumption that comets were a warning from the gods gripped Western civilization for two millennia after the heyday of the ancient Greeks. Even at the close of the 20th century, comets and meteors play starring roles in cinematic tales of doom and destruction. The comet threat, it turns out, is not merely mythological. Modern science has revealed that a giant collision probably did in the dinosaurs, and in 1994 human beings nervously watched Comet Shoemaker-Levy 9 smash into Jupiter.

In light of their ominous reputation, it is ironic to consider that such far-flung space debris might be responsible for making Earth the pleasant, life-covered planet it is today. Since the early 1960s, space scientists have speculated that comets and other remnants of solar system formation hauled in gas and water molecules and that these components provided the atmosphere and oceans that made the planet habitable. A growing number of investigators, including our team at the Astrochemistry Laboratory at the National Aeronautics and Space Administration Ames Research Center, now believe that



COMPLEX ORGANIC MOLECULES—some like those found in living things—abound in dark parts of interstellar clouds. More than four billion years ago one such cloud collapsed into a swirling disk that spawned the sun and planets. Some of the fragile molecules survived the violent heat of solar system formation by sticking together in comets at the disk's frigid fringe. Later the comets and other cloud remnants carried the molecules to Earth.

COMETS AND ASTEROIDS heavily bombarded Earth until about four billion years ago. Even now the planet sweeps up hundreds of tons of dust and meteorites from these objects every day. Many of the dust particles (*photograph*)—most only a thousandth of a millimeter across—are rich in organic molecules fabricated in the dark cloud that spawned the solar system. The voids in the particle below presumably once contained ice that evaporated when the dust escaped its parent comet.



JOHN P. BRADLEY *MVA Inc.*

DUST PARTICLE

SLIM FILMS

some important raw materials needed to build life also hitched a ride from space. Some of these extraterrestrial organic molecules formed leaky capsules that could have housed the first cellular processes. Other molecules could have absorbed part of the sun's ultraviolet radiation, thereby sheltering less hardy molecules, and could have helped convert that light energy into chemical food.

In this scenario, the stage for life was set more than four billion years ago when a cold, dark interstellar cloud collapsed into the swirling disk of fiery gas and dust that spawned our solar system. Earth coalesced not long after the sun, about 4.5 billion years ago, and was long thought to have retained water and the ingredients for life since then. Many scientists today, however, suspect that its earliest days were hot, dry and sterile. It is now clear that space debris bombarded the young planet, creating cataclysms equivalent to the detonation of countless atomic bombs. In fact, the moon may be a chunk of Earth that was blown off in a collision with an object the size of Mars [see "The Scientific Legacy of Apollo," by G. Jeffrey Taylor; SCIENTIFIC AMERICAN, July 1994]. Impacts of this kind, common until about 4.0 billion years ago, surely aborted any fledgling life struggling to exist before that time.

As new research is pushing forward the day the planet became habitable, other discoveries are pushing back the first signs of life. Microfossils found in ancient rocks from Australia and South Africa demonstrate that terrestrial life was certainly flourishing by 3.5 billion years ago. Even older rocks from Greenland, 3.9 billion years old, contain isotopic fingerprints of carbon that could have belonged only to a living organism. In other words, only 100 million years or so after the earliest possible point when Earth could have safely supported life, organisms were already well enough established that evidence of them remains today. This narrowing window of time for life to have emerged implies that the process might have required help from space molecules.

Origins of Origins

The planet's first single-celled organisms presumably owe their primeval debut to a series of chemical steps that led up to carbon-rich molecules such as amino acids. Under the right conditions, the amino acids linked into chainlike proteins, the building blocks of life. One of the first researchers to show how these jump-starter amino acids might have originated was Stanley L. Miller, a graduate student in Harold C. Urey's University of Chicago laboratory in the early 1950s. Miller, now at the University of California at San Diego, sent sparks akin to lightning through a primitive "atmosphere" of simple hydrogen-rich molecules enclosed in a glass flask. Over a few weeks' time, the reaction yielded an array of organic molecules—among them amino acids—in a second flask simulating ocean water below.

New evidence has drawn the components of Miller's atmosphere into question, but his primordial soup theory for how life's ingredients were spawned in a warm pond or ocean on the planet's surface still has a strong following. Some scientists have recently moved the soup pot to the seafloor, where they say murky clouds of minerals spewing from hot springs may have generated life's precursor molecules. But a growing group of other researchers are looking at an altogether different source for life-giving molecules: space.

Juan Oró of the University of Houston suggested extraterrestrial input in 1961, and Sherwood Chang at NASA Ames revived the theory in 1979. Since 1990 Christopher R. Chyba of the Search for Extraterrestrial Intelligence (SETI) Institute in Mountain View, Calif., has been the premier advocate of the idea that small comets, meteorites and interplanetary dust particles transported the planet's water and atmospheric gases from space.

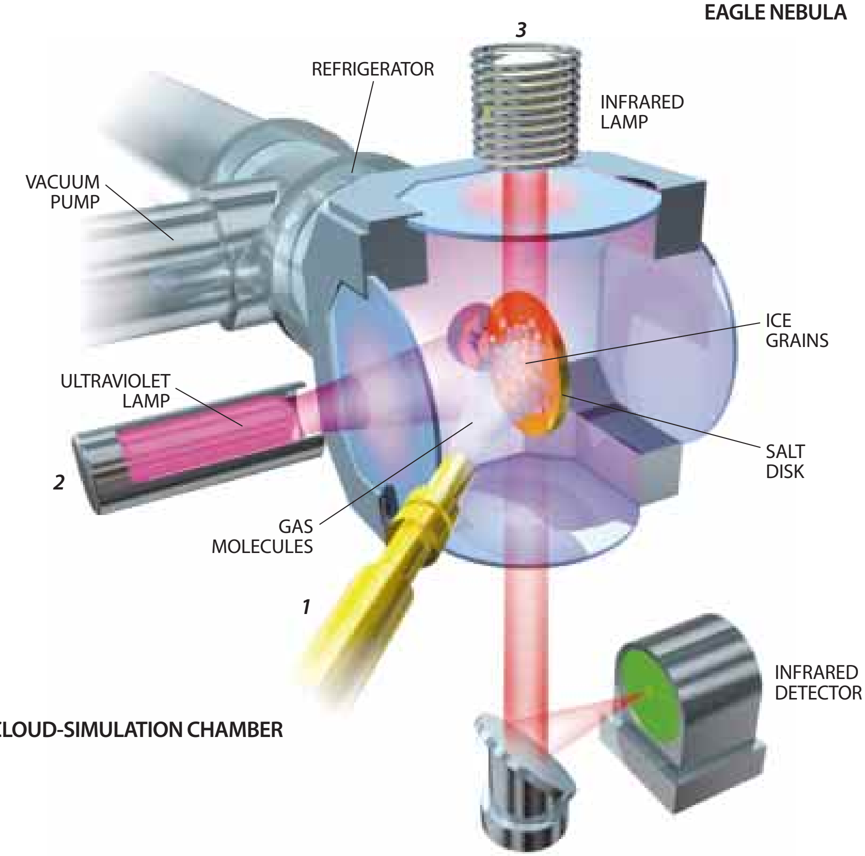
Not all scientists agree about how Earth got its oceans, but most concur that space debris contributed. Hundreds of tons of dust alone are estimated to drift down to the planet's surface every day. These tiny flecks—the largest no bigger than a grain of sand—litter the inner solar system and sometimes streak across the night sky as shooting stars. Growing evidence now argues that in addition to hauling in the gases and water that made the planet habitable, comets and their cousins peppered the primordial soup with ready-made organic molecules of the kind seen in living systems today.

Recent observations of comet celebrities Halley, Hale-Bopp and Hyakutake revealed that these icy visitors are rife with organic compounds. In 1986 cameras on board the Giotto and Vega spacecrafts captured images of dark material on Halley's surface that resembles the coallike kerogen in some meteorites, and mass spectrometers caught glimpses of carbon-rich molecules. More recently, ground-based telescopes inspecting the coma and tail of comets Hyakutake and Hale-Bopp distinguished a number of specific organic compounds, including methane and ethane. Several space probes will explore other comets during the next 20 years [*see box on page 48*].

When a comet passes through the warm inner solar system, part of it boils away as gas and dust, some of which is later swept up by Earth's gravitational pull. NASA scientists snag comet particles in the upper atmosphere using ER2 aircraft that fly twice as high as a typical commercial jetliner. At altitudes of 62,000 feet, the space dust sticks to oil-

JEFF HESTER AND PAUL SCOWEN *Arizona State University* AND NASA

EAGLE NEBULA



CLOUD-SIMULATION CHAMBER

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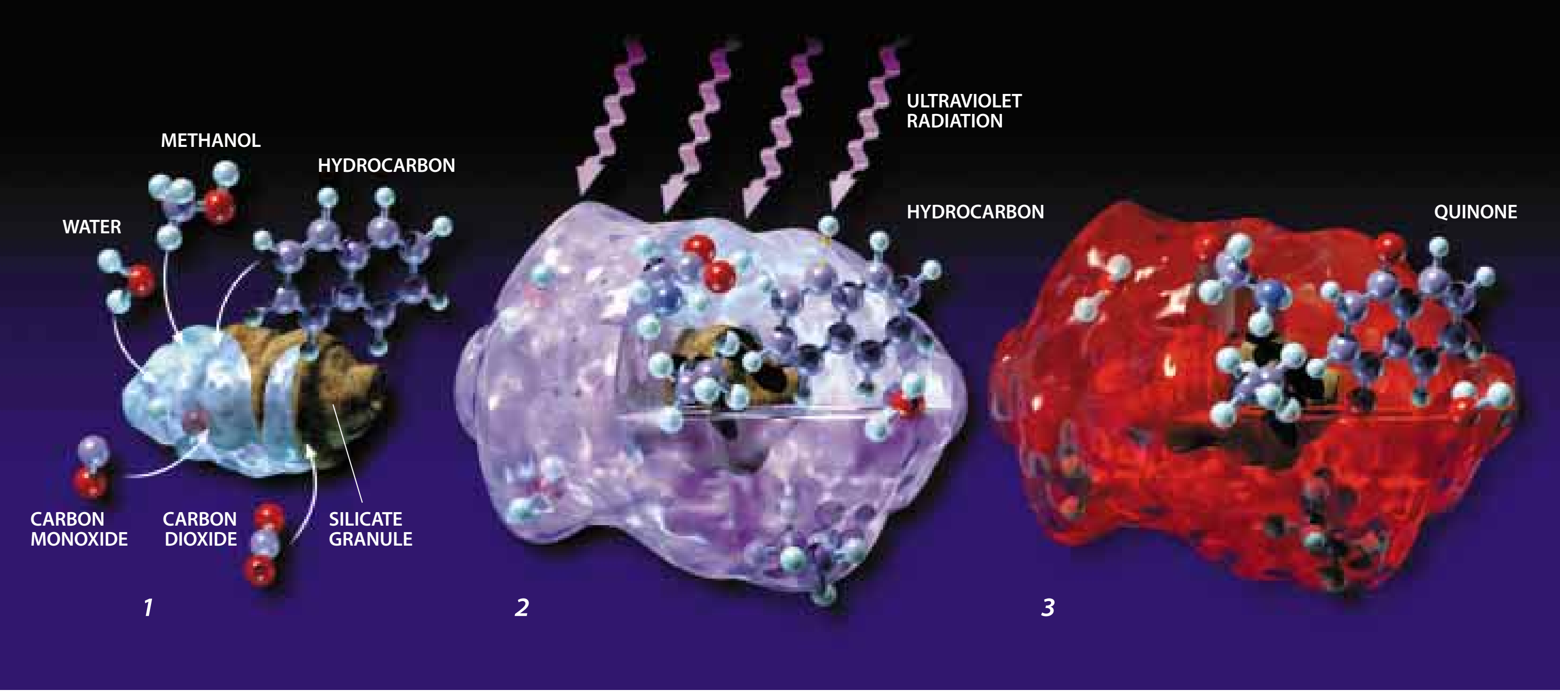
LABORATORY SIMULATIONS mimic what happens in the cold parts of interstellar clouds such as the Eagle Nebula (*above right*). Inside a shoebox-size metal chamber (*right*), a special refrigerator and pump generate the subzero vacuum of space. A mist of simple gas molecules sprayed from a copper tube freezes onto a salt disk, which acts as the silicate core of an ice grain in space (*1*). An ultraviolet lamp bathes the newly formed ice in a potent dose of starlike radiation (*2*). Infrared light, also emitted by stars, is later projected through the ice to determine what molecules are frozen inside (*3*). Comparison of infrared absorption spectra reveals that the composition of the laboratory ice is strikingly similar to that of ice in the clouds.



INTERSTELLAR ICE begins to form when molecules such as water, methanol and hydrocarbon freeze to sandlike granules of silicate drifting in dense interstellar clouds (*1*). Ultraviolet radiation from nearby stars breaks some of the chemical bonds of the frozen compounds as the ice grain grows to no bigger than about one ten-thousandth of a millimeter across (*2*). Broken molecules recombine into structures such as quinones, which would never form if the fragments were free to float away (*3*).

SLIM FILMS

coated plastic plates inside collectors under the plane's wings. One of us (Sandford), among other researchers who analyzed these microscopic particles, found that some contain as much as 50 percent organic carbon, more than any other known extraterrestrial object. Even composed of only 10 percent carbon on average, space dust brings about 30 tons of organic material to Earth every day.

Better understood than distant comets and microscopic dust are the large chunks of asteroids that actually smack into Earth as meteorites. Made up mostly of metal and rock, some meteorites also bear compounds such as nucleobases, ketones, quinones, carboxylic acids, amines and amides. Of the slew of complex organics extracted from meteorites, the 70 varieties of amino acids have attracted the most attention. Only eight of these amino acids are part of the group of 20 employed by living cells to build proteins, but those of extraterrestrial origin embody a trait intrinsic to Earthly life.

Amino acids exist in mirror-image pairs, a molecular quality called chirality. Just as a person's hands look alike when pressed palm to palm but different when placed palm to knuckles, individual amino acids are either left-handed or right-handed. For little-known reasons and with rare exceptions, amino acids in living organisms are left-handed. One criticism of Miller-type experiments is that they produce equal numbers of both forms. This is where extraterrestrial amino acids come out ahead. Since his first report in 1993, John R. Cronin of Arizona State University has demonstrated a slight surplus of left-handedness in several amino acids extracted from two different meteorites. Some researchers believe life's left-handedness is by chance, but extraterrestrial starting ingredients may have predetermined this molecular peculiarity.

Amino acids may be the most biologically relevant carbon molecules in meteorites, but they are not the most abundant. Most of the carbon is tied up in kerogen, a material composed partly of polycyclic aromatic hydrocarbons, compounds perhaps best known as carcinogenic pollutants on Earth. A product of combustion found in soot, grilled hamburgers and automobile exhaust, these special hydrocarbons also caused a stir when they were detected in the controversial Martian meteorite ALH 84001, which some scientists think harbors evidence of fossilized Martian microbes.

Icebox or Firestorm?

Although it is clear that comets, meteorites and dust carry interesting molecules to Earth, finding out where these molecules originated has been tougher to determine. Some scientists have suggested that reactions in liquid water trickling through the parent comets or through asteroids of some meteorites are partly responsible for their rich organic chemistry. But these reactions could hardly account for the carbon molecules frozen in dark interstellar clouds.

Scientists increasingly believe that comet ice is a remnant of the dark cloud that collapsed into the fiery solar nebula, the swirling disk of gas and dust that gave birth to the sun and planets. The ice has remained unchanged because it stayed protected in the deep freeze at the system's fringe. Other scientists still assert an older claim that extraterrestrial organic molecules were born within the nebula. According to this theory, ice from the mother cloud boiled off, and molecules broke apart and were rearranged in the violence of planet formation.

Molecules tortured in the solar nebula, and only later frozen into comets, should bear the isotopic signatures common to planets and other objects in the inner solar system. On the contrary, most comet dust is enriched in rare elements such as deuterium (an isotope of hydrogen with one extra neutron). Deuterium enrichment is a characteristic of chemical reactions in the low-temperature environment of interstellar space. Out where temperatures hover just above absolute zero, there is enough energy to shake apart only a few of the molecules made from the heavier isotopes, so they tend to build up over time.

The true origin of most comets and meteorites almost certainly combines the pure interstellar icebox and the nebular firestorm. This duality is manifest in space dust comprising materials that have been altered by great heat right next to others that have not. Still, a barrage of evidence during the two years since the observations of comets Hale-Bopp and Hyakutake has bolstered the case for comets' interstellar heritage. For example, dozens of researchers have detected striking similarity between specific molecules and deuterium enrichments in comets and those commonly observed in interstellar ice grains. In addition, the spin state of hydrogen atoms—a measure of the conditions the ice has experienced—in water from comet Hale-Bopp confirms that the ice formed at, and was never warmed above, approximately 25 kelvins (–400 degrees Fahrenheit).

If comet ice came from an interstellar cloud, it is easy to believe that organic molecules did, too. Astronomers see signatures of a range of organic compounds throughout the universe, especially among the clouds. For example, a decade of research conducted by one of us (Allamandola) and others has revealed that polycyclic aromatic hydrocarbons are the most abundant class of carbon-bearing compounds in the universe, trapping as much as 20 percent of the total galactic carbon in their molecular lattices.

Deducing the composition of microscopic particles of dust and ice hundreds of light-years away is possible in part through astronomical observations of clouds such as the Eagle Nebula. Dark clouds absorb some of the infrared radiation from nearby stars. When the remaining radiation reaches detectors on Earth and is spread out into a spectrum, light missing at certain wavelengths corresponds to particular chemical bonds with the capacity to absorb light.

Clouds in the Lab

By comparing the infrared spectra of clouds in space with similar measurements of interstellar ice analogues made in the laboratory, our group at NASA Ames and several other teams around the world determined that the ice grains in the dark clouds are frozen on cores of silicate or carbon. The ice is composed primarily of water but often contains up to 10 percent simple molecules such as carbon dioxide, carbon monoxide, methane, methanol and ammonia.

We wanted to understand how these very simple and abundant interstellar molecules undergo reactions in the ice that transform them into the more complicated compounds seen in meteorites. Allamandola, who had trained as a cryogenics chemist, decided to build an interstellar cloud in the laboratory.

Refrigerators and pumps generate a frigid vacuum of space inside a metal chamber about 20 centimeters (about eight inches) on a side. A mist of simple gas molecules sprayed from a copper tube freezes onto a lollipop-size disk of aluminum or cesium iodide, which plays the role of the space grain's core. To make the environment of the interstellar cloud complete, a small ultraviolet lamp projects starlike radiation into the chamber.

Our experiments reveal that even at the extremely low temperatures and pressures of space, the ultraviolet radiation breaks chemical bonds just as it does in Earth's atmosphere. There the radiation is infamous for breaking apart chemicals such as chlorofluorocarbons, whose newly freed atoms attack the protective ozone molecules that keep the radiation from baking the planet down below.

Raw Materials or Real Life?

Life's raw materials riding to Earth on comets and meteors is a far cry from living organisms drifting in from space and colonizing the planet—an ancient idea known as panspermia. After 17th-century Italian physician Francesco Redi debunked the long-standing view that life springs out of nonliving matter, it was assumed that life could only come from life. Following this logic, Swedish chemist and Nobel laureate Svante A. Arrhenius proposed in 1908 that radiation from stars could blow microscopic germs from one world to another.

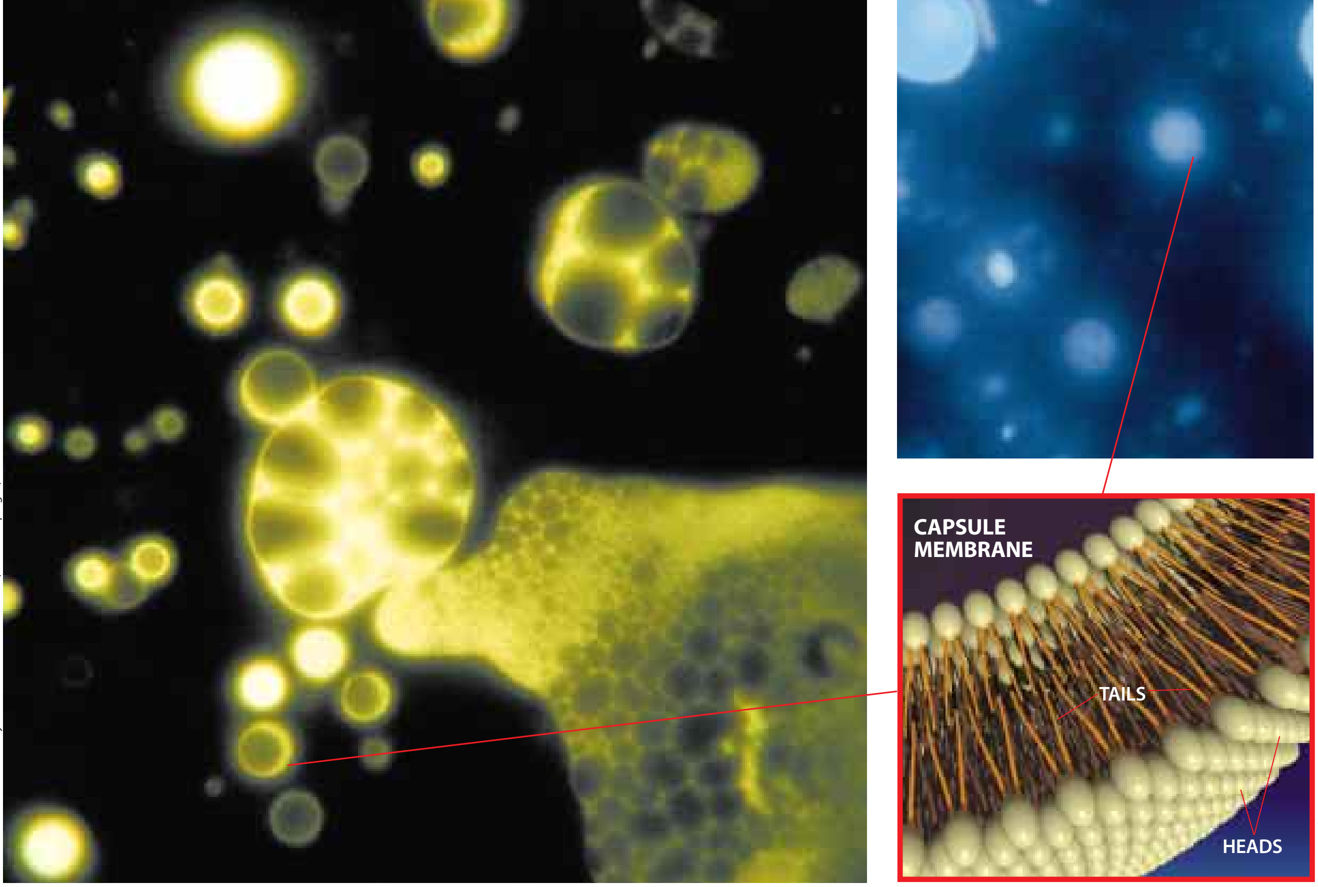
Few other scientists have been willing to contemplate such extraterrestrial colonization—until recently. Controversial reports of fossil microbes in Martian meteorite ALH 84001 enlivened the panspermia theory in 1996, and a report the same year suggested that the inner planets may have exchanged tons of debris in the past few billion years. Still, few scientists believe that life ever arose on Mars, let alone that Martian organisms could have survived the 80-million-kilometer trip to Earth. Even if a microbe could endure the impact that flung it into space, deadly radiation and the subzero vacuum of space during thousands of years of travel would very likely destroy it.

In this light, colonization from Mars seems unnecessarily complicated when life could just as well have started here on Earth. Or perhaps life arose independently on Mars if it possessed life-friendly conditions sometime in the past. After all, the comets and meteors that seeded Earth with water and organic molecules would have provided the same service to the entire solar system.

This December a new NASA probe will search the Martian soil for signs of life. But even if life turns up on the Red Planet, proving that those organisms survived a trip from their home planet and settled on Earth is another story. —*M. P. B.*

JET PROPULSION LABORATORY/NASA

Martian landscape in 1997



DAVID W. DEAMER *University of California at Santa Cruz (left and top right)*

SLIM FILMS

HYDROCARBONS FROM SPACE might have sheltered life's precursor molecules. Hydrocarbons from meteorites (*green*)—and similar compounds made in the laboratory under interstellar conditions (*blue*)—organize themselves into leaky capsules when mixed in water. The molecules' hydrophilic, or water-loving, heads point toward the outside of the capsule membrane, while their hydrophobic tails stay tucked inside (*bottom right*). The spheres also fluoresce, indicating that carbon-rich compounds are trapped inside.

In space, when atoms are locked in ice, this bond-breaking process can make molecular fragments recombine into unusually complex structures that would not be possible if these segments were free to drift apart. Everywhere in space where these ice grains are seen, complex compounds are forming—especially in the ultraviolet-rich regions around young stars. In our cloud chamber, we bathe the growing ice grain in radiation equal to what a space grain would endure in thousands of years.

When one of us (Bernstein) started with a simple ice of frozen water, methanol and ammonia—in the same proportions seen in space ice—the experiment yielded complex compounds such as the ketones, nitriles, ethers and alcohols found in carbon-rich meteorites. We also created hexamethylenetetramine, or HMT, a six-carbon molecule known to produce amino acids in warm, acidic water. Molecules with as many as 15 carbon bonds also showed up in the mix.

Some of these compounds display a curious tendency that may have housed the activities of early life. David W. Deamer, a chemist at the University of California at Santa Cruz, found that some of the molecules in the cloud-chamber ice grains form capsulelike droplets in water. These capsules are strikingly similar to those that he produced 10 years ago using extracts of the meteorite from Murchison, Australia. When Deamer mixed organic compounds from the meteorite with water, they spontaneously assembled into spherical structures similar to cell membranes. Our colleague Jason Dworkin has shown that these capsules are made up of a host of complex organic molecules.

For this self-organization to occur, the molecules usually have a dozen carbon atoms or more, and they must be amphiphilic. That means that their hydrophilic, or water-loving, heads line up facing the water, while their hydrophobic tails stay tucked away inside the membrane. Bubbles in both the mete-

Comet Missions in the Works

Stardust
First comet sample from deep space
A probe will fly through the gaseous coma of **comet Wild 2** in 2004 and will use a silicon-based substance called aerogel to collect dust samples that it will return to Earth in 2006.
Launch: February 7, 1999 (NASA)

Space Technology 4/Champollion
First comet landing
A satellite orbiting **comet Tempel 1** will send a small vehicle to land on the comet's rocky nucleus in 2005. The lander will take photographs and analyze subsurface samples.
Launch: 2003 (NASA)

Rosetta
Most thorough comet study ever
A satellite will rendezvous with **comet Wirtanen** in 2013 and will spend 11 months making measurements from orbit while a lander probes the comet's surface.
Launch: 2003 (European Space Agency)

orite and cloud-chamber extracts also fluoresce, indicating that additional organic material is trapped inside.

Of the compounds we produce, those of perhaps the greatest biological significance are made when we start with water ices embedded with the polycyclic aromatic hydrocarbons known to be abundant in the clouds. Under interstellar conditions, the hydrocarbons convert to many of the components of carbon-rich meteorites, including more complex alcohols, ethers and, perhaps most significantly, quinones. Ubiquitous in living systems today, quinones can stabilize unpaired electrons, an ability living cells need for various energy-transfer activities. For example, the active ingredients in aloe and henna are quinones.

The electron-transport ability of these versatile molecules plays an essential role in converting light into chemical energy in modern photosynthesis. This ability proves more intriguing in the early-Earth scenario when coupled with the quinones' ability to absorb ultraviolet radiation—a grave danger to fragile molecules such as amino acids. Extraterrestrial quinones may have acted as ultraviolet shields before Earth's protective ozone layer developed. In addition, they may have been the molecules that the planet's first life-forms used to trap light for the primitive precursor of photosynthesis.

From Molecules to Life

We know from laboratory experiments and astronomical observations that the seemingly barren conditions of deep space generate complex organic compounds that meteorites and dust bring to us even today. Reconsidering the emergence of life in this light, we can see that the arrival of amino acids, quinones, amphiphilic molecules and other extraterrestrial organics may well have made it possible for life to flourish or at least may have facilitated its development. Perhaps extraterrestrial amino acids built the first proteins, and perhaps amphiphilic molecules housed the light-harnessing capacity of the quinones, but the exact roles these organic compounds played is not clear. Extraterrestrial organics may have been nothing more than starting materials for chemical reactions that produced other molecules entirely.

One can imagine that a molecule, literally dropped from the sky, could have jump-started or accelerated a simple chemical reaction key to early life. If life's precursor molecules really linked up in a primordial soup, amino acids from space may have provided the crucial quantities to make those steps possible. Likewise, life-building events taking place on the seafloor might have incorporated components of extraterrestrial compounds that were raining into the oceans. Being able to carry out this chemistry more efficiently could have conferred an evolutionary advantage. In time, that simple reaction would become deeply embedded in what is now a biochemical reaction regulated by a protein.

Of course, a huge gap still yawns between even the most complex organic compounds and the genetic code, metabolism and self-replication that are crucial to the definition of life. But given their omnipresence, if organic molecules from space had something to do with life here, that means they were—and always are—available to help with the development of life elsewhere.

Hints of life-friendly conditions on Mars and under the icy surface of Jupiter's moon Europa suggest that other places in our solar system may have benefited from extraterrestrial input. The ubiquity of complex organic molecules across space, combined with the recent discoveries of planets around other stars, also makes it more likely that the conditions conducive to life, if not life itself, have developed in other solar systems as well. SA

QUINONES FROM SPACE have structures nearly identical to those that help chlorophyll molecules transfer light energy from one part of a plant cell to another.

The Authors

MAX P. BERNSTEIN, SCOTT A. SANDFORD and LOUIS J. ALLAMANDOLA work in the Astrochemistry Laboratory at the National Aeronautics and Space Administration Ames Research Center. Bernstein is a contractor to NASA Ames and a member of the Search for Extraterrestrial Intelligence Institute in Mountain View, Calif. He simulates the organic chemistry of comets and interstellar ice grains and ponders their connection to the origins of life. Sandford and Allamandola are both civil servants at NASA Ames. Sandford performed seminal work on interplanetary dust particles, is an associate editor of the journal *Meteoritics and Planetary Science* and is a co-investigator in NASA's Stardust mission. Allamandola, the founder and director of the Ames Astrochemistry Laboratory, has 20 years' experience in pioneering studies of interstellar and solar system ices and is an originator of the polycyclic aromatic hydrocarbon hypothesis.

You can read more about the authors and their research at http://web99.arc.nasa.gov/~astrochm/ on the World Wide Web.

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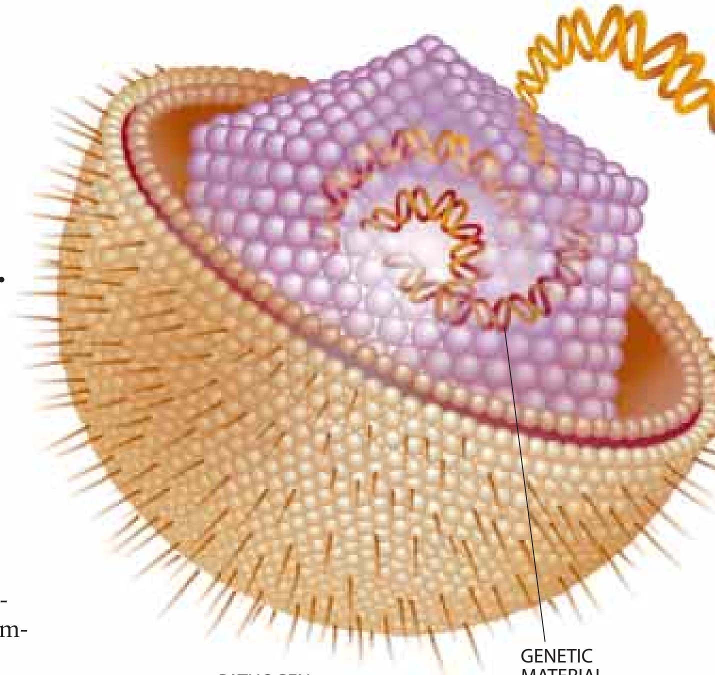
Genetic Vaccines

Vaccines crafted from genetic material might one day prevent AIDS, malaria and other devastating infections that defy current immunization technologies. They may even help treat cancer

by David B. Weiner and Ronald C. Kennedy



Vaccines arguably constitute the greatest achievement of modern medicine. They have eradicated smallpox, pushed polio to the brink of extinction and spared countless people from typhus, tetanus, measles, hepatitis A, hepatitis B, rotavirus and other dangerous infections. Successful vaccines have yet to be introduced, however, for too many deadly or debilitating disorders—among them, malaria, AIDS, herpes and hepatitis C. This gap exists because standard immunization methods work poorly or pose unacceptable risks when targeted against certain illnesses.

Clearly, alternate strategies are needed. One of the most promising creates vaccines out of genetic material, either DNA or RNA. In the past 10 years such vaccines have progressed from a maligned idea to entities being studied intensively in academia and industry and in early human trials.

Vaccines at Work

The merits of genetic immunization become most apparent when the actions of traditional vaccines are understood. Traditional preparations consist primarily of a killed or a weakened version of a pathogen (disease-causing agent) or of some piece (subunit) of the agent. As is true of most genetic vaccines under study, standard types aim to prime the immune system to quash dangerous viruses, bacteria or parasites quickly, before the pathogens can gain a foothold in the body. They achieve this effect by tricking the immune system into behaving as if the body were already beset by a microorganism that was multiplying unabated and damaging tissues extensively.

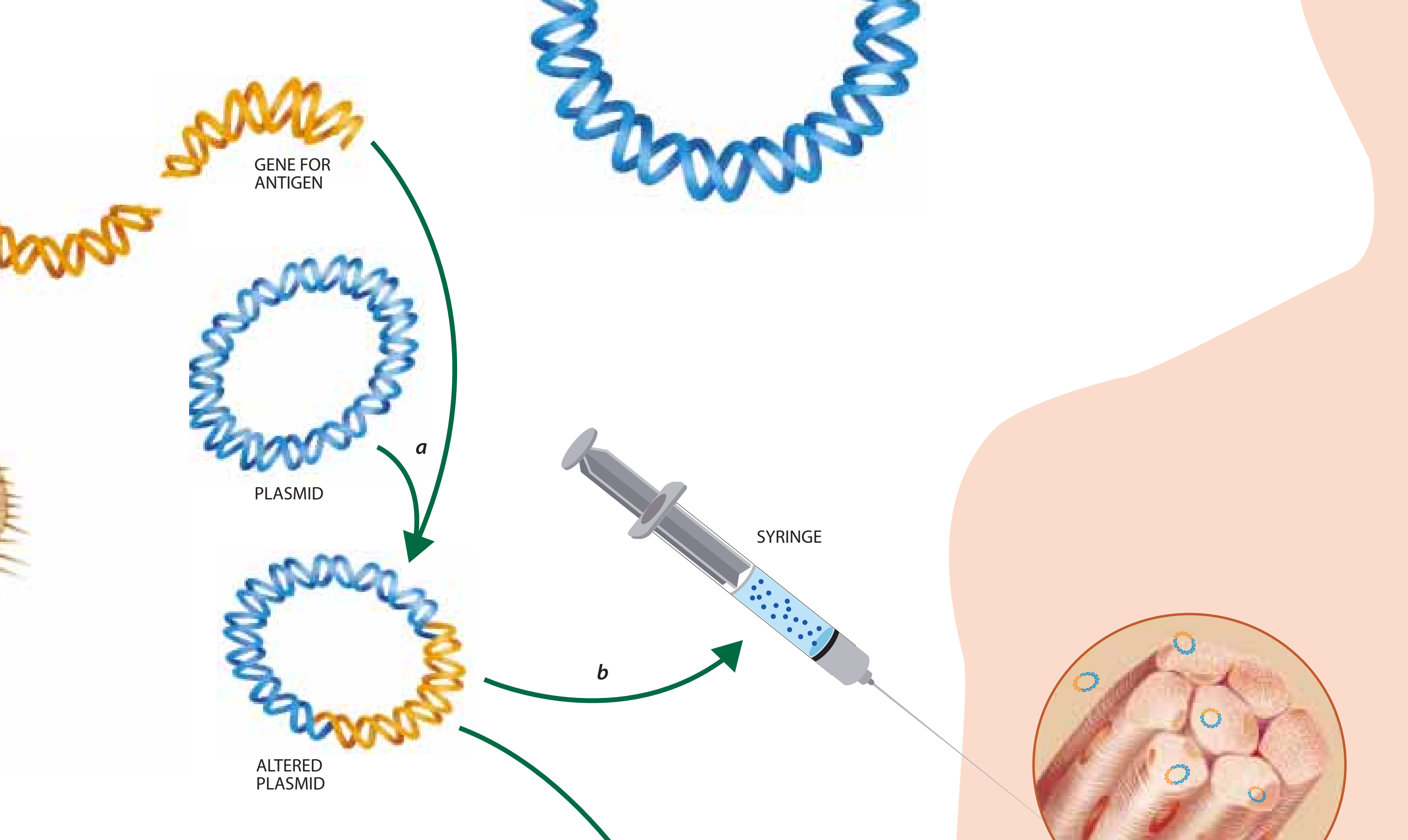
When responding to a real infection, the immune system homes in on foreign antigens—substances (usually proteins or protein fragments) that are produced uniquely by the causative agent and not by a host. Two major arms can come into play, both of which receive critical help from white blood cells known as helper T lymphocytes. The humoral arm, led by B lymphocytes, acts on pathogens that are outside cells. These B cells secrete antibody molecules that latch onto infectious agents and thereby neutralize them or tag them for destruction by other parts of the immune system. The cellular arm, spearheaded by cytotoxic (killer) T lymphocytes, eradicates pathogens that colonize cells. Infected cells display bits of their attacker's proteins on the cell surface in a particular way. When cytotoxic T lymphocytes "see" those flags, they often destroy the cells—and the infiltrators within.

Beyond eliminating invaders, activation of the immune system against a specific pathogen leads to the creation of memory cells that can repel the same pathogens in the future. Vaccines confer protection by similarly inducing immune responses and the consequent formation of memory cells.

But standard vaccines vary in the kind and duration of security they provide. Those based on killed pathogens (such as the hepatitis A and the injected, or Salk, polio vaccines) or on antigens isolated from disease-causing agents (such as the hepatitis B subunit vaccine) cannot make their way into cells. They therefore give rise to primarily humoral responses and do not activate killer T cells. Such responses are ineffective against many microorganisms that infiltrate cells. Also, even when nonliving preparations do block disease, the protection often wears off after a time; consequently, recipients may need periodic booster shots.

Attenuated live vaccines, usually viruses, do enter cells and make antigens that are displayed by the inoculated cells. They thus spur attack by killer T lymphocytes as well as by antibodies. That dual activity is essential for blocking infection by many viruses and for ensuring immunity when investigators do not know whether a humoral immune response would be sufficient by itself. What is more, live vaccines—such as the measles, mumps, rubella, oral polio (Sabin) and smallpox types—frequently confer lifelong immunity. For those reasons, they are considered the "gold standard" of existing vaccines.

Live vaccines can be problematic in their own way, however. Even they can fail to shield against some diseases. Those that work can cause full-blown illness in people whose immune system is compromised, as in cancer patients undergoing chemotherapy, AIDS suf-

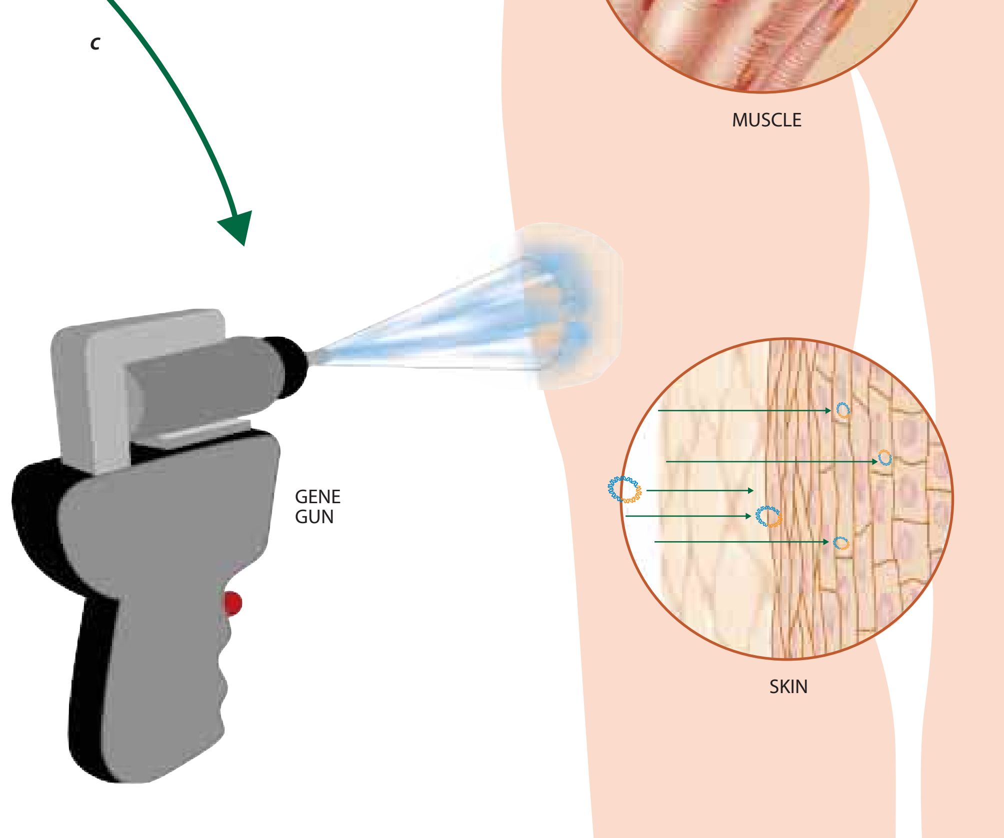


ferers and the elderly. Such individuals may also contract disease from healthy people who have been inoculated recently. Moreover, weakened viruses can at times mutate in ways that restore virulence, as has happened in some monkeys given an attenuated simian form of HIV, the virus that causes AIDS. For some diseases, the risks of reversion to virulence are intolerable.

Whole-organism vaccines, whether live or dead, have other drawbacks as well. Being composed of complete pathogens, they retain molecules that are not involved in evoking protective immunity. They can also include contaminants that are unavoidable by-products of the manufacturing process. Such extraneous substances sometimes trigger allergic or other disruptive reactions.

The Best of All Worlds

Genetic vaccines are quite different in structure from traditional ones. The most studied consist of plasmids—small rings of double-stranded DNA originally derived from bacteria but totally unable to produce an infection. The plasmids used for immunization have been altered to carry genes specifying one or more antigenic proteins normally made by a selected pathogen; at the same time, they exclude genes



MAKING OF A GENETIC VACCINE usually involves isolating one or more genes from a disease-causing agent (pathogen) and splicing those genes into plasmids (*a*), closed rings of DNA. The rings are then delivered into small groups of cells, often by injection into muscle cells (*b*) or by propulsion into the skin via a so-called gene gun (*c*). The chosen genes code for antigens—substances able to elicit an immune response—that are normally made by the pathogen.

DANA BURNS-PIZER

that would enable the pathogen to reconstitute itself and cause disease.

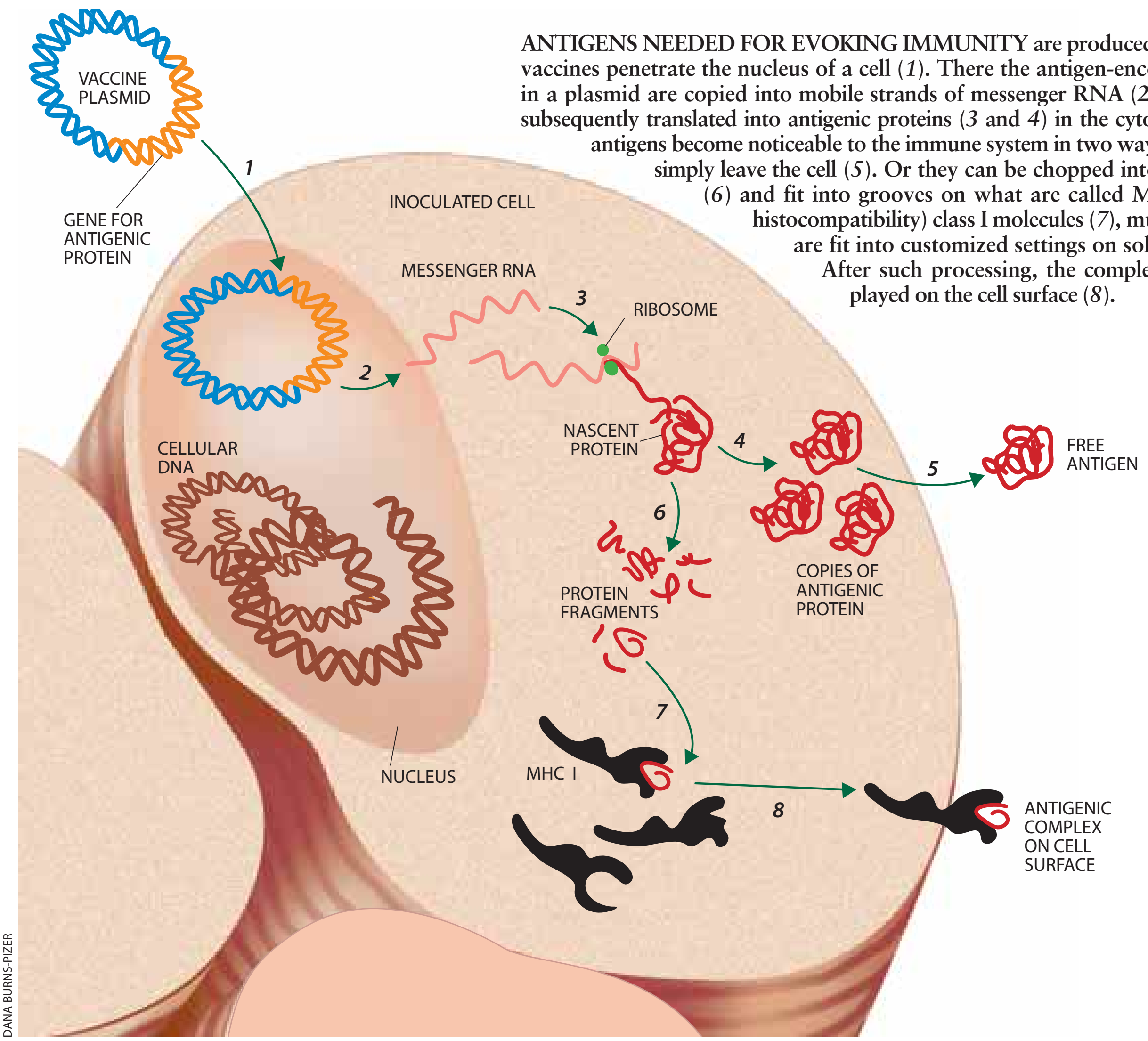
The vaccines usually are delivered by injection or by a device known as a gene gun. Injection, commonly into muscle, puts genes directly into some cells and also leads to uptake by cells in the vicinity of the inserted needle. The gene gun propels plasmids into cells near the surface of the body—typically those of the skin or mucous membranes. Once inside cells, some of the recombinant plasmids make their way to the nucleus and instruct the cell to synthesize the encoded antigenic proteins. Those proteins can elicit humoral (antibody-type) immunity when they escape from cells, and they can elicit cellular (killer-cell) immunity when they are broken down and properly displayed on the cell surface (just as occurs when cells harbor an active pathogen).

Such features raise hopes that, once perfected for use in people, DNA vaccines will preserve all the positive aspects of existing vaccines while avoiding their risks. In addition to activating both arms of the immune system, they will be unable to cause infection, because they will lack the genes needed for a pathogen's replication. As a bonus, they are easy to design and to generate in large quantities using now commonplace recombinant DNA technology, and they are as stable as other vaccines (perhaps more so) when stored. They should therefore be relatively inexpensive to manufacture and to distribute widely. Further, because they can be engineered to carry genes from different strains of a pathogen, they can potentially provide immunity against several strains at once, something that should be very helpful when the microorganism is highly variable, as in the case of influenza viruses and HIV.

Some investigators are testing vaccines composed of RNA, a single-stranded relative of DNA. RNA in cells leads readily to synthesis of any encoded proteins. RNA, however, is less stable than DNA, a property that can be problematic for vaccine manufacture and distribution. These difficulties are probably surmountable. Nevertheless, because RNA vaccines have been studied much less extensively than the DNA types, we will concentrate our discussion on DNA vaccines.

Lemonade from Lemons

The idea that genes might serve as vaccines grew in part out of research begun almost half a century ago. In the 1950s and 1960s experiments unrelated to vaccine development showed that delivery of genetic material into an animal's cells could trigger some synthesis of the encoded proteins as well as of antibodies targeted against those proteins. Thereafter, workers occasionally assessed antibody manufacture as an easy way to demonstrate that a given gene was generating a protein.



ANTIGENS NEEDED FOR EVOKING IMMUNITY are produced after DNA vaccines penetrate the nucleus of a cell (*1*). There the antigen-encoding genes in a plasmid are copied into mobile strands of messenger RNA (*2*), which are subsequently translated into antigenic proteins (*3* and *4*) in the cytoplasm. The antigens become noticeable to the immune system in two ways. They can simply leave the cell (*5*). Or they can be chopped into fragments (*6*) and fit into grooves on what are called MHC (major histocompatibility) class I molecules (*7*), much as gems are fit into customized settings on solitaire rings. After such processing, the complexes are displayed on the cell surface (*8*).

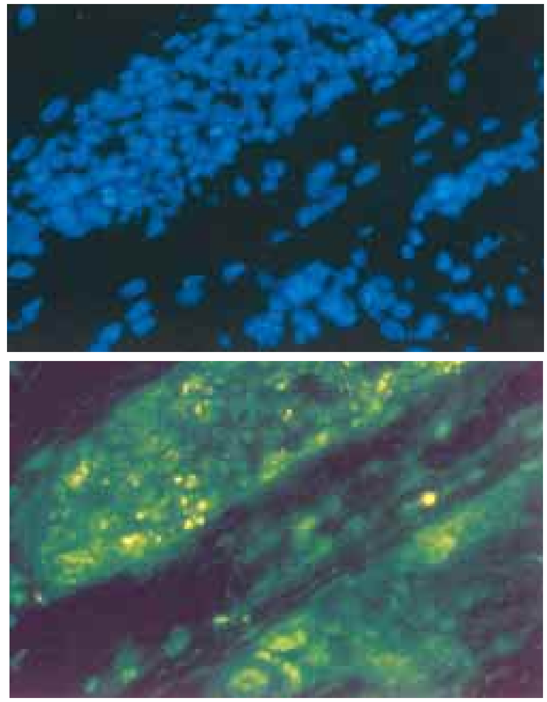
In the 1970s and early 1980s the ability of inserted genes to prompt an immune response gained attention from other researchers, this time as a disappointing phenomenon. Scientists trying to develop gene therapy (the delivery of genes to correct inherited and other disorders) noted that proteins made from therapeutic genes were sometimes destroyed in animals receiving the genes. The reason: an immune reaction to unfamiliar proteins.

By the early 1990s a handful of laboratories had begun exploring whether the unwanted immune responses to the protein products of foreign genes might be put to good use—for vaccination. Many others were dubious at first, skeptical, for instance, that the immunity elicited would be strong enough to spare people from infection by a living pathogen.

Yet in 1992 a cluster of animal studies done by independent groups demonstrated resoundingly that the concept was sound. Those groups included teams led by Stephen A. Johnston of the University of Texas Southwestern Medical Center in Dallas; by Philip Felgner of Vical in San Diego and Margaret Liu, then at Merck in West Point, Pa.; by Harriet L. Robinson, then at the University of Massachusetts; and by one of us (Weiner) at the University of Pennsylvania.

Collectively, those studies and a host of others conducted over the next few years revealed that DNA vaccines delivered into cells could stimulate the immune system of rodents and primates to generate B cell, cytotoxic T cell and helper T cell responses against many different pathogens and even against certain cancers. The research showed as well that immune responses and disease protection could be elicited when different routes of administration were used. The responses, moreover, could be enhanced by a variety of methods for facilitating DNA uptake by cells.

Since the mid-1990s many more researchers have turned their attention to DNA vaccines, and the technology has advanced to the first rung of human trials, focused on safety. The earliest trial began in 1995, when plasmids containing HIV genes were delivered to patients already infected by that virus. Bigger trials initiated in 1996 made history in another way. For the first time, physicians put new genes (coding for HIV or influenza proteins) into healthy people, instead of into those afflicted by some disorder.



PHOTOGRAPHS BY VELPANDI AYYAVOO *University of Pennsylvania*

MUSCLE CELLS, identified by a blue marker (*top*), were made to glow green (*bottom*) after being injected with a DNA vaccine carrying a gene from the human immunodeficiency virus (HIV). The green indicates that the cells manufactured the HIV protein specified by the viral gene. Such micrographs constitute some of the proof that DNA vaccines can generate the proteins needed for evoking immune responses.

So far human tests are examining vaccines designed to prevent various infections (by HIV, herpes, influenza, hepatitis B and *Plasmodium*—the parasite responsible for malaria), to bolster the impaired immunity of patients already infected with HIV and to treat a number of cancers (among them lymphomas and malignancies of the prostate and colon). Although cancer is not an infectious disease, much evidence indicates that harnessing the body's immune defenses may help combat it.

The safety trials ask such questions as, are the plasmids toxic, and does DNA delivered as a drug incite an immune response against the body's own DNA? Encouragingly, the studies have not identified any serious side effects to date.

Such trials do not assess disease prevention or amelioration, but many are monitoring the vaccines' effects on the immune system. Preliminary findings hint that useful immune responses can be achieved. Notably, HIV vaccines have generated both humoral and cellular responses; plasmids bearing *Plasmodium* antigens have evoked significant cellular immune responses; and a vaccine against hepatitis B has resulted in levels of antibodies that should be high enough to prevent infection. In common with traditional vaccines, though, current genetic approaches will probably have to be combined in many cases with generalized immune stimulators (adjuvants) in order to elicit the strong immune responses required to shield recipients from future infections.

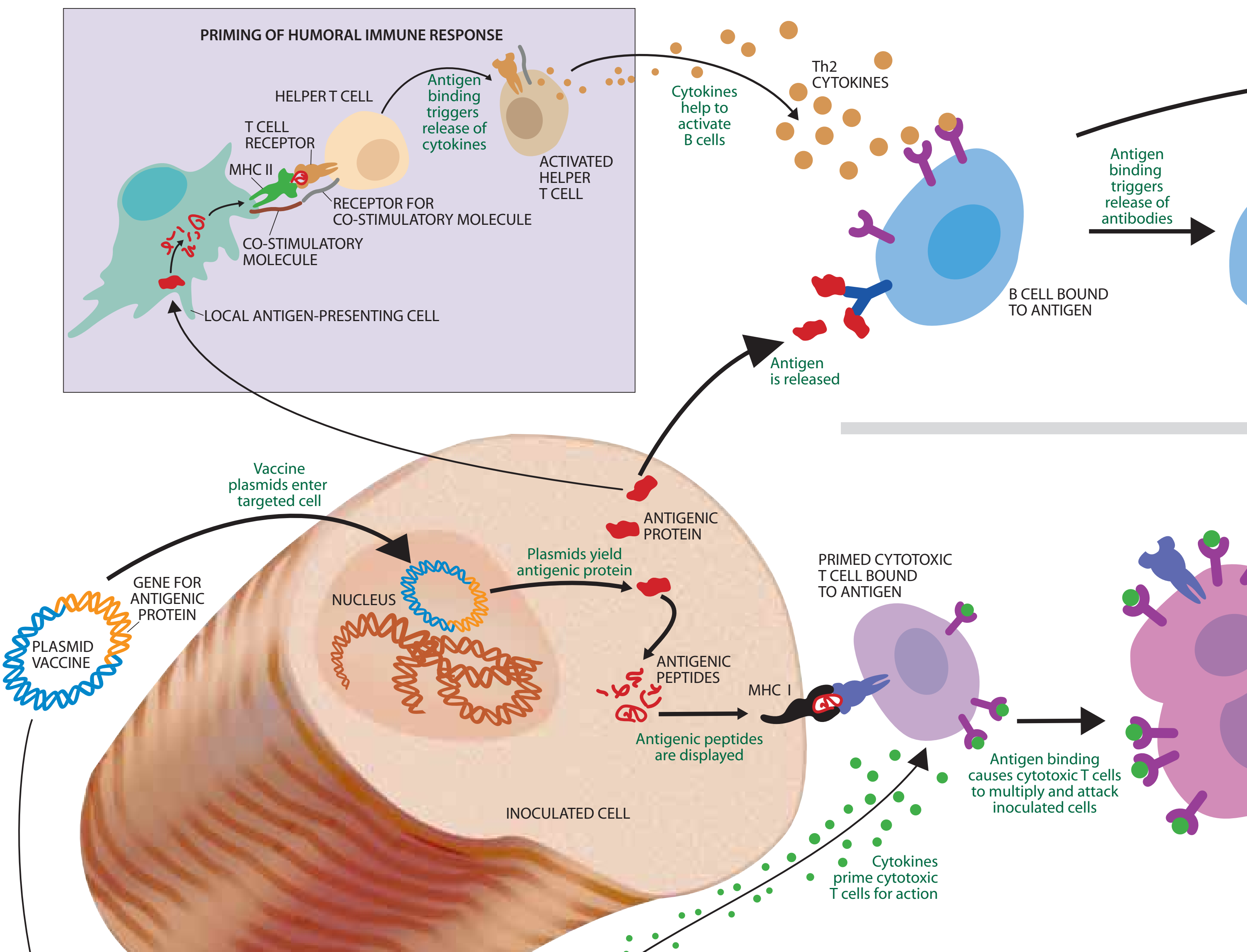
How Do the Vaccines Work?

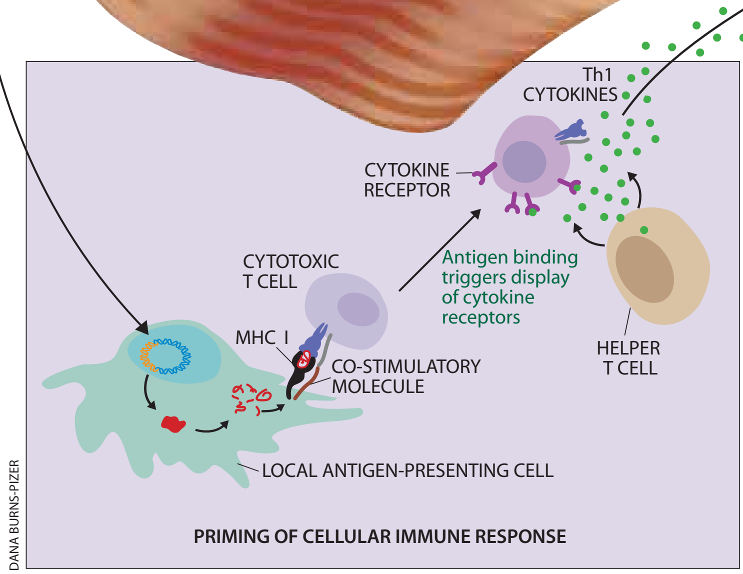
As clinical trials continue, bench scientists are seeking deeper insight into exactly how genetic immunization stimulates immunity, especially by the often crucial cellular arm of the defensive system. A detailed understanding should offer clues to enhancing effectiveness.

In truth, for many years immunologists faced a paradox. DNA vaccines obviously activated killer T cells. Yet simply putting DNA into skin or muscle cells and prompting those cells to display fragments of the encoded antigens should not have produced that outcome. Before such display can activate cytotoxic T cells, the killers must be primed, or switched on, in part by interacting in a specific way with what are called "professional" antigen-presenting cells. In particular, the T cells must bind to the same antigenic fragments they will detect on inoculated nonimmune cells (such as muscle) and, simultaneously, to a second, co-stimulatory molecule (a "second signal") ordinarily found only on antigen-presenting cells.

At one time, biologists thought DNA vaccines had no way of getting into antigen-presenting cells and therefore that those cells had no way of synthesizing and displaying the antigens encoded by those vaccines. Recent discoveries by several groups have shown, however, that the original view was mistaken. Some of the plasmids do in fact make their way into professional antigen-presenting cells. These cells then display antigens alongside the critical co-stimulatory molecules and help to prepare the T cells for action [*see illustration on next two pages*]. Such findings indicate that to induce a powerful cellular immune response, DNA vaccines must be deliv-

How DNA Vaccines Work

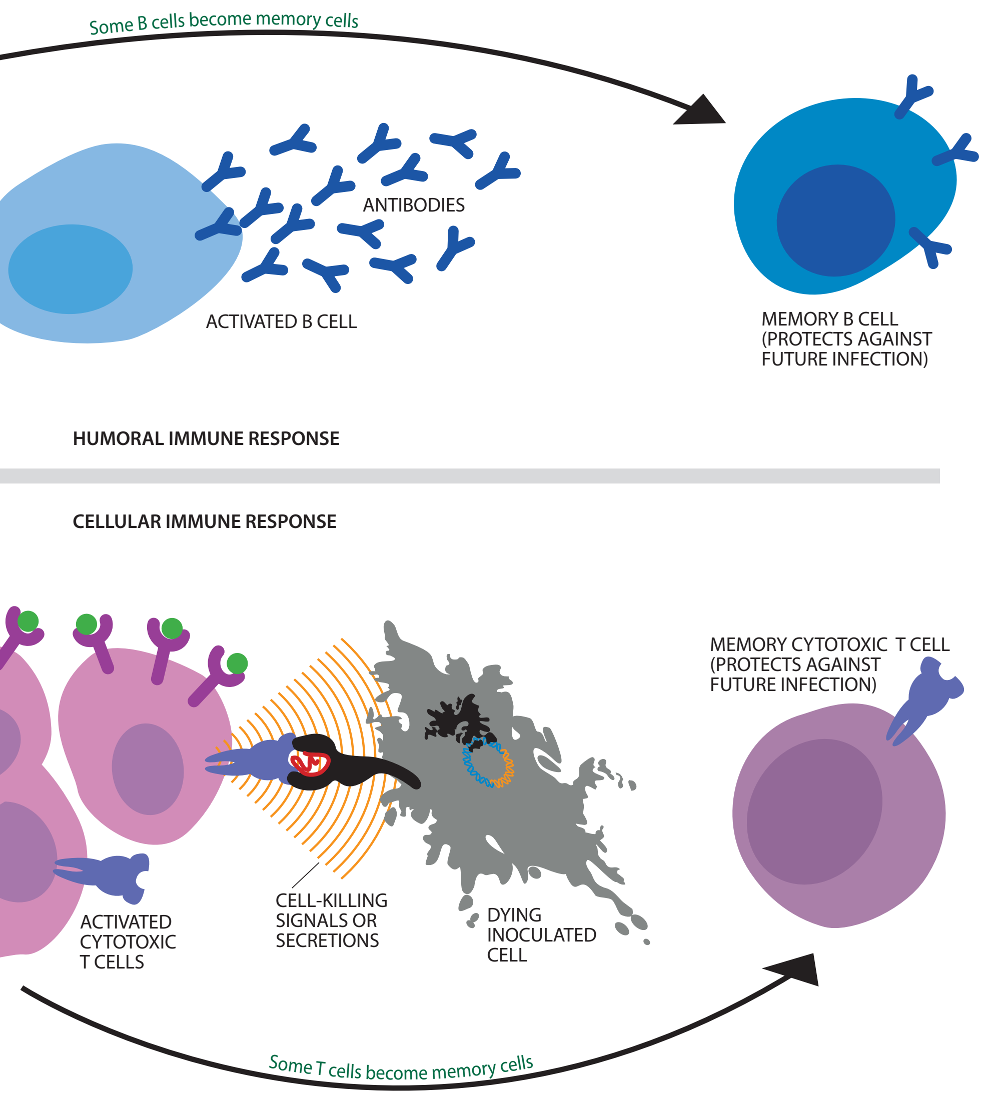




DNA vaccines elicit protective immunity against an infectious agent, or pathogen, primarily by activating two branches of the immune system: the humoral arm, which attacks pathogens outside of cells, and the cellular arm, which eliminates cells that are colonized by an invader. Immunity is achieved when such activity generates long-lasting "memory" cells—the sentries that stand ready to stop the pathogen from causing disease.

A simplified description of how the vaccines induce immunity begins at the far left of the diagram, with entry of a DNA vaccine into a targeted cell, such as muscle, and the cell's subsequent production of antigens normally found on the pathogen of interest. In the humoral response (*top unboxed sequence*), white blood cells called B cells bind to released copies of antigenic proteins and then multiply. Many of the progeny secrete antibody molecules that during an infection would glom onto the pathogen and mark it for destruction. Other offspring become the memory cells that will quell the pathogen if it circulates outside cells.

Meanwhile display of antigenic protein fragments, or peptides, on inoculated cells (within grooves on MHC class I



molecules) can trigger a cellular response (*bottom unboxed sequence*). Binding to the antigenic complexes induces white blood cells known as cytotoxic (killer) T cells to multiply and kill the bound cells and others displaying those same peptides in the same way. Some activated cells will also become memory cells, ready to eliminate cells invaded by the pathogen in the future.

In actuality, several preliminary steps must occur before such responses can arise. To set the stage for B cell activation (*top box*), "professional" antigen-presenting cells (APCs) must ingest antigen molecules, chop them and display the resulting peptides on MHC class II molecules. Helper T cells, in turn, must recognize both the peptide complexes and "co-stimulatory" molecules found only on the professional antigen presenters. If those steps occur, the helper cells may secrete signaling molecules known as Th2 cytokines, which help to activate B cells bound to antigens.

Priming of cytotoxic T cell responses involves APCs as well (*bottom box*). Before the cytotoxic cells can respond to antigens on inoculated cells, APCs have to take up vaccine plasmids, synthesize the encoded antigens, and exhibit fragments of the antigens on MHC class I molecules along with co-stimulatory molecules. Then the killer T cells must recognize those signals and also be hit by cytokines (this time of the Th1 type) from helper T cells. In steps not shown, DNA vaccines also yield memory helper T cells needed to support the defensive activities of other memory cells. —*D.B.W. and R.C.K.*

ered in a way that will yield good uptake by antigen-presenting cells, not only by other cell types.

Separate work suggests that the plasmid DNA surrounding antigenic genes is more than a mere gene-delivery vehicle; it strengthens the immune response evoked by the antigens. This effect apparently stems from the high frequency of CG sequences in plasmids. Each strand in the DNA double helix is built from units called nucleotides that are distinguished by the bases they contain—either adenine (A), cytosine (C), guanine (G) or thymine (T). Plasmid DNA, derived from bacteria, has a greater frequency of CG sequences than does the DNA in vertebrates. Moreover, the CG units in bacterial plasmids tend to have no methyl group attached, whereas those in vertebrates generally are methylated.

Investigators have proposed that the vertebrate body interprets a high frequency of unmethylated CG pairs as a danger signal. In response, a relatively primitive part of the immune system (one not dependent on antigen recognition) attempts to destroy or wall off the foreign intruder.

Engineering for Optimal Effect

Along with analyzing the natural behavior of genetic vaccines in the body, immunologists are looking ahead, exploring ideas for increasing overall immune reactivity and for optimizing the ratio of cellular to humoral responses. One proposal for amplifying responsiveness has emerged from studying the DNA around CG sequences. Researchers have demonstrated that plasmid DNA yields the most potent immune response when CG sequences are flanked by two purines (adenine or guanine) to their "C" side and two pyrimidines (thymine or cytosine) to their "G" side. In mice, plasmids containing such "immunostimulatory sequences" induced more vigorous antibody and cytotoxic T cell activity than did an otherwise identical vaccine. Hence, increasing the number of immunostimulatory sequences in plasmids might well amplify the immunogenicity of the antigenic codes in a DNA vaccine.

A different approach is incorporating genes for signaling molecules called cytokines into antigen-carrying plasmids or into separate plasmids. Cells of the immune system release these molecules to regulate their own, and one another's, activities. As an example, a molecule named granulocyte-macrophage colonystimulating factor stimulates the proliferation of antigen-presenting cells, among other actions. Inclusion of its gene has been shown to boost overall responses to DNA vaccines.

To ensure that genetic vaccines trigger a strong cellular response when needed, researchers are experimenting specifically with genes for cytokines that are known to promote killer-cell activity. In mice, scientists have found that helper T cells called Th1 cells secrete cytokines that favor cellular responses at the expense of humoral (antibody) ones, whereas other helper cells (Th2 cells) secrete cytokines that favor humoral activity. In humans, helper T cells seem to come in more varieties, but a preponderance of Th1-type cytokines still promotes a cellular response, and a preponderance of Th2-type cytokines stimulates a humoral response.

One such project showed that a vaccine including genes for HIV antigens and for interleukin-12 (a classic Th1 cytokine) reduced production of anti-HIV antibodies in mice and markedly enhanced the responsiveness of cytotoxic T cells to HIV antigens. This bias toward a cellular response is particularly encouraging, because recent findings by HIV researchers indicate that a potent killer T cell response to HIV is critically important for combating HIV replication.

Genes for substances known as chemokines might be incorporated as well. Chemokines are small molecules that attract both antigen-presenting cells and T cells to damaged or infected tissues. Like cytokines, these substances differ in the mix of cells on which they act and in the precise effects they exert. As their individual actions are better understood, carefully combining specific chemokine genes with selected cytokine genes could go far toward customizing both the type and the extent of immune responses elicited.

DNA vaccines could in theory even sidestep the need for classical antigen-presenting cells to prime cytotoxic T cells. If a gene for an antigen were bundled with a gene for a co-stimulatory molecule normally made by an antigen-presenting cell, then inoculated skin, muscle or other cells would themselves display both the antigen and the crucial "second signal," thereby facilitating both the priming and the activation of cytotoxic T cells.

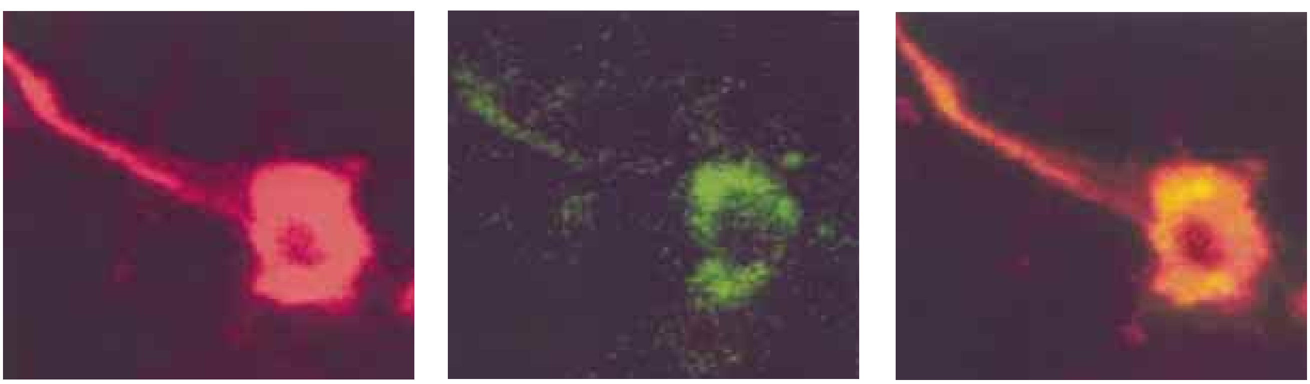
Getting from Here to There

If first-generation genetic vaccines do well in clinical trials, they may sometimes be combined initially with more traditional vaccines to achieve even better effects. Let us say, for example, that a subunit vaccine (consisting of a protein) evoked a good antibody response against a pathogen but that a cellular response was needed as well. Meanwhile a new DNA vaccine proved able to induce a cellular response but did not excite an ideal antibody response. In a so-called prime-boost strategy, physicians might deliver the DNA vaccine and then boost the antibody response by later delivering the subunit vaccine as well. Eventually, though, as vaccine makers learn how to optimize responses to genetic immunization (such as through the techniques described above), manufacturers may be able to achieve the needed effects by constructing genetic vaccines alone.

As the exciting, futuristic possibilities of genetic immunization are being considered, those of us who are captivated by this technology also have to roll up our sleeves and grapple with a great many details. For instance, most DNA vaccines stop yielding much protein after about a month. Would finding a way to extend plasmid survival lead to stronger immunity, or would it backfire and encourage attacks against unvaccinated, healthy tissue? How long does immunity last in human beings? How much do people vary in their responses? Which doses are most effective and what kinds of delivery schedules are best? We also need to know which substances are most useful for targeting genetic material to specific cells (including to antigen-presenting cells) and for enhancing the cellular uptake of plasmids. And which genes, out of the sometimes thousands, in a given pathogen should be selected for maximal power?

Clinical trials answering these questions and assessing the effectiveness of the first generation of DNA vaccines may not be completed for five or 10 years. Whether those specific versions reach the market, though, genetic immunization technologies are likely to prove extremely valuable for research into the basic biology of the immune response and for the design of even better vaccines.

Vaccine makers today often have little idea of which components of the immune system need to be activated most strongly against a given pathogen and which antigens and other substances can achieve that stimulation. Now, however, they can readily mix and match antigenic and other genes (such as those for



PHOTOGRAPHS BY MICHAEL CHATTERGOON
University of Pennsylvania

UPTAKE OF DNA VACCINES by antigen-presenting cells, a crucial event in the induction of immunity, has now been demonstrated by several groups. In one approach, scientists added two kinds of labels to cells in a snippet of tissue that was exposed to a DNA vaccine—one tag (*red at left*) marked antigen-presenting cells; another (*green at center*) denoted any cells making an antigen specified by the vaccine. When images of the cells were superposed, the appearance of an orange color (*right*) signified the presence of antigen-presenting cells that had taken up the vaccine and produced the encoded protein.

Human Trials of DNA Vaccines

This table lists many of the human tests known to the authors. All candidate vaccines are in early-stage trials examining safety and immune responses, and all have been well tolerated. No trials of effectiveness for disease prevention or treatment have begun. Most of the studies are ongoing.

Vaccine Objective	Proteins Encoded by Vaccine Genes	Immune Results So Far
Hepatitis B prevention	Hepatitis B surface antigen	Humoral and cellular responses
Herpes simplex prevention	Herpes glycoprotein	Immune analyses in progress
HIV prevention	Envelope and regulatory proteins; or core proteins and enzymes involved in HIV replication	Cellular responses (ultimately, all the genes will probably be tested in one vaccine)
Influenza prevention	Hemagglutinin	Immune analyses in progress (trial has ended)
Malaria prevention	Circumsporozoite protein	Cellular responses
HIV therapy	Envelope and regulatory proteins; or tat, nef and regulatory proteins	Humoral responses in first trial in list (which has ended); cellular responses in other trial
HIV therapy	Envelope, regulatory and core proteins and enzymes involved in HIV replication	Vaccine was combined with aggressive drug therapy (HAART); immune analyses in progress
Therapy for adenocarcinomas of the breast and colon	Carcinoembryonic antigen (CEA)	Cellular responses
Therapy for B cell lymphoma	Immunoglobulin	Humoral responses
Therapy for cutaneous T cell lymphoma (CTCL)	T cell receptor	Immune analyses in progress (trial has ended)
Therapy for prostate cancer	Prostate-specific membrane antigen	Immune analyses in progress

HEIDI NOLAND

cytokines and chemokines) in experimental DNA vaccines and compare the success of different combinations in small animals quite quickly. In that way, they can simultaneously gain a handle on the immune responses that are needed for protection and on the antigens and other proteins that can generate them.

As part of this testing, some researchers are creating "libraries" of a pathogen's genes; an individual library contains every gene in the organism, with each gene spliced into its own plasmid. They then deliver subsets of such libraries to animals, which are also exposed to the live pathogen. Next, they identify the subsets that work best, further subdivide the groups and do more testing, until the most useful mix of antigens emerges.

As the years go by, the inherent manipulability of DNA should make it a vehicle of choice for teasing apart the body's complex immune responses to different disease-causing agents. With such information in hand, vaccine makers should be able to design vaccines that will channel immune responses down selected pathways. In the past, manufacturers had no way to custom-tailor their products easily and inexpensively. In the future, such "rationally" designed genetic vaccines are likely to provide new immune therapies for cancer and powerful ways to prevent or minimize any number of devilish infections that elude human control today. SA

The Authors

DAVID B. WEINER and RONALD C. KENNEDY have each contributed significantly to the development of genetic vaccines. Weiner, a pioneer in the study of antiviral DNA vaccines, is associate professor of pathology and laboratory medicine and a member of the Institute of Human Gene Therapy at the University of Pennsylvania. Kennedy, professor of microbiology and immunology and of obstetrics and gynecology at the University of Oklahoma Health Sciences Center, studies genetic vaccines against cancer as well as those targeted against infectious agents.

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The Mystery of Nucleon Spin

A new generation of experiments promises to pin down more of the still uncertain internal structure of protons and neutrons

by Klaus Rith and Andreas Schäfer

Protons and neutrons were among the first subatomic particles discovered this century. They reside in the nuclei of atoms and are hence known as nucleons; they make up more than 99.9 percent of the matter in the everyday world around us, including this page and you yourself. (The other 0.1 percent is electrons.) Eighty years of experimental study and theoretical analysis have taught us much about the nucleons, yet certain of their fundamental properties still hold puzzles and surprises. For the past decade, physicists have labored to resolve a particular quandary known as the spin crisis.

This crisis emerged from the highly successful quark model of subatomic particles. Theorists developed this model as a neat, compact description of the myriad of new particles detected during the 1950s and 1960s, as well as of old familiars such as the proton and neutron. The properties and interactions of the particle zoo fell into patterns that could be explained by their being made of just three species of quark, called up, down and strange.

A proton consists of two up quarks and one down quark; a neutron has one up and two downs. Many of the nucleons' properties can be derived by combining properties of their constituent quarks in an elementary way. For example, the electric charge of a proton is exactly the sum of its quarks' fractional charges: $+1 = 2/3 + 2/3 - 1/3$. Attempts to observe individual quarks all failed, however, and many physicists considered quarks to be no more than a mathematical convenience—a bookkeeping system for describing interactions but not "real" objects that could be studied.

At the end of the 1960s, a collaboration of physicists from the Massachusetts Institute of Technology and the Stanford Linear Accelerator Center (SLAC) studied the inner structure of nucleons by passing a high-energy beam of electrons through liquid hydrogen. Because a hydrogen nucleus is a lone proton, this operation is almost as good as firing electrons at pure protons. From the details of the electrons' deflections, the structure of the proton is deduced.

Similar experiments had been carried out before, and all had revealed the proton to be essentially a spherical, "soft" blob of charge. To everyone's astonishment, at the higher energies made available by the new SLAC accelerator some of the electrons were scattered, as if they were striking tiny, hard points of charge within the protons. At first the experimenters thought that they had made a mistake or that some subtle effect was to blame. But the results were true: the first evidence of quarks as real objects.

Today we know that nucleons contain an incessant dance of evanescent particles flickering in and out of existence. Some of these are gluons, the particles that produce the strong force. The three main quarks that make up a nucleon—known as the valence quarks—exchange gluons back and forth, and the effect is like a strong, rubbery glue that holds them together [see "Glueballs," by Frank E. Close and Philip R. Page; Scientific American, November 1998]. Along with the three valence quarks and the gluons, short-lived "virtual" quarks and antiquarks materialize and vanish in pairs, contributing to the nucleon's properties [*see illustration on opposite page*].

A property of tremendous importance is spin, a form of innate angular momentum. All the particles that make up a nucleon have spin, and somehow the spins of all these whirling dervishes must add up to the observed total spin of a nucleon. At first glance, the three-quark model of a nucleon seems to account for its spin tidily: two of the quarks could have opposite spins, which cancel, and the spin of the remaining quark could produce precisely the observed spin of a nucleon. It is plausible that all the gluons and virtual quark-antiquark pairs should have spins that add up, on average, to zero. But reality is not that simple.

In the mid-1980s experimental results indicated that essentially *none* of a nucleon's spin was attributable to its quarks' spins. That surprise birthed the "spin crisis." An intense theoretical effort was launched to reconcile theory and experiment. Another surprise was that strange quarks, usually considered exiled to the domain of exotic, short-lived particles and high-energy interactions, seem to play a sizable role in the spin structure of the everyday nucleon.

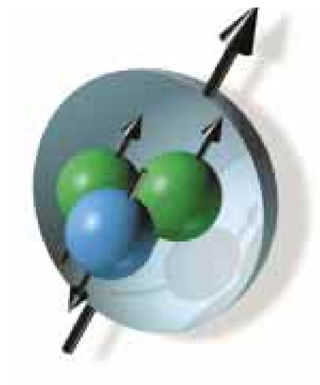
Today theorists believe they know how those features come about, and the experimental effort is entering a new era as laboratories in Europe and the U.S. probe the spin structure of nucleons with novel techniques and greater precision. It remains to be seen whether the results will confirm our understanding or generate fresh mysteries—and another "crisis."

The Importance of Spin

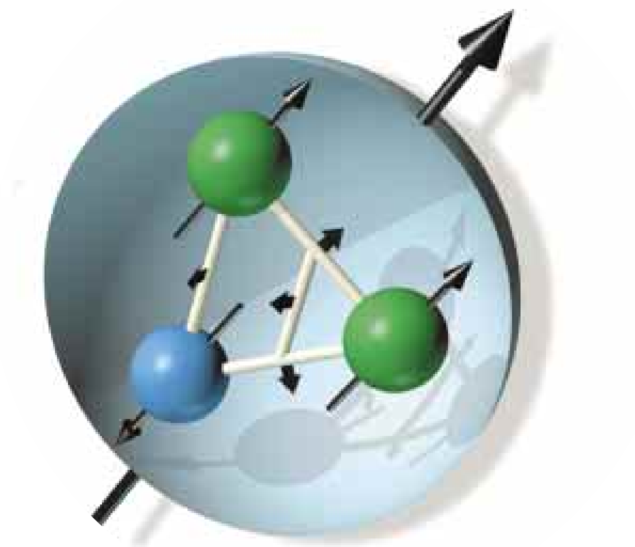
Anything that rotates or moves around a fixed point has angular momentum. The earth, for example, has orbital angular momentum from its yearly circuit around the sun and intrinsic angular momentum from its daily rotation on its axis. The spin of a fundamental particle corresponds to intrinsic angular momentum but has special quantum properties. Quantum mechanics requires spin to come only in multiples of a tiny fundamental quantity called

Four Views of a Proton

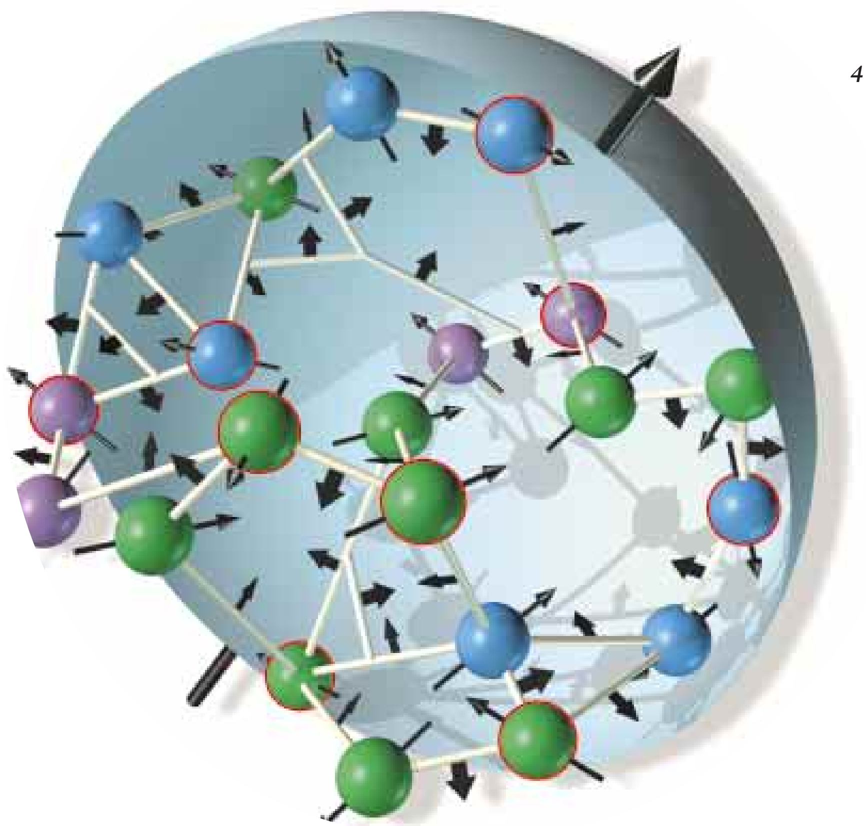
1 At low resolution the proton appears to be a "soft" blob (*gray*), about 2×10^{-15} meter in diameter, with a charge of +1 and an angular momentum, or spin, of ½ (*arrow*). For a spinning object, the arrow would point along the axis of rotation, so that the rotation would appear to be clockwise viewed along the arrow. Quantum particles have an innate spin of fixed magnitude that is distinct from the everyday notion of an object rotating.



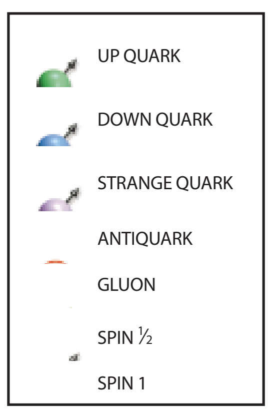
2 The quark model describes the proton as the sum of two up quarks (*green*) and one down quark (*blue*), whose individual charges and spins add up to the proton's properties. Each quark has a spin of ½, but the total spin will also be ½ if, for example, two of the quark spins cancel by being oppositely oriented.



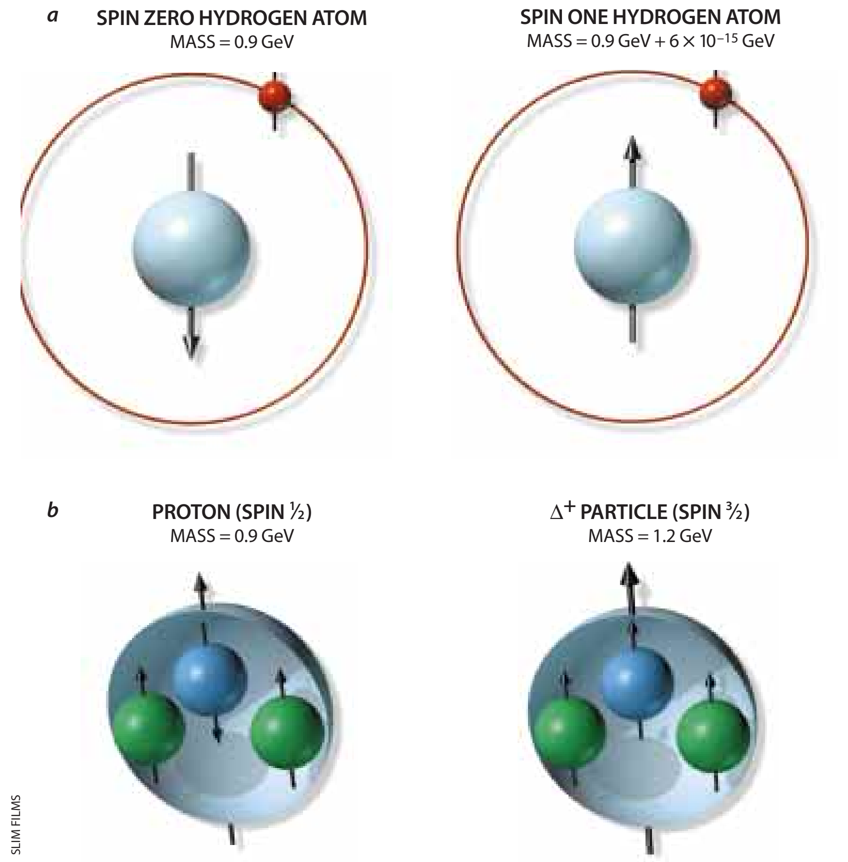
3 Experiments at the end of the 1960s revealed quarks to be essentially point particles within the proton, and the theory of quantum chromodynamics (QCD) described the force holding them together, illustrated here as a kind of elastic cord (*white*). The cord is a manifestation of particles (gluons) that each have a spin of one. The motion of the quarks and gluons within the proton can also contribute angular momentum to the proton spin.



4 The full quantum description of QCD adds a complicated, flickering dance of virtual quarks and antiquarks (*red outline*), including strange quarks (*purple*) not usually considered a part of ordinary matter. This snapshot of a single configuration only hints at the full quantum uncertainties and dynamic fluctuations. The details of how this dance produces the spin of the proton are still too difficult to be calculated reliably and are only gradually being revealed by experiment.



SLIM FILMS



SPIN STRUCTURE has a greater effect in subatomic particles than in atoms. In a hydrogen atom (*a*), aligning the spins of the proton (*gray*) and the electron (*red*) increases the atom's total spin from zero to one, but its mass by only a few millionths of an electron volt. The Δ^+ particle and the proton (*b*) each consist of two up quarks and one down quark and differ only in their spin, but this makes the Δ^+ 30 percent heavier than the proton.

Planck's quantum of action, $\hbar$ (pronounced "h-bar").

Only integer and half-integer multiples are allowed, and all the relatively familiar particles of matter—electrons, protons, neutrons and quarks—have the smallest possible nonzero quantity of spin, one half of $\hbar$. It is customary to say these particles have a spin of 1/2.

Spin is crucial in determining how a particle behaves. For example, if electrons had any spin other than 1/2, the way that they stack into orbitals around an atom would be radically altered. The periodic table of elements and all of chemistry would be mutated beyond recognition.

Calculating the spin of a composite particle by adding up the angular momenta of its components is not as simple as adding up electric charges, because each angular momentum has an orientation associated with it. The orientation of the earth's spin, for example, is represented by an arrow running along the earth's axis, pointing from south to north.

Nonetheless, computing such sums for an atom, even one with dozens of electrons, is well understood and is the kind of task physics students solve in quantum mechanics courses. Unfortunately, no one has succeeded with the analogous computations for the quarks and gluons that make up protons and neutrons.

The Trouble with QCD

The problem lies in the theory that describes the strong force, known as quantum chromodynamics, or QCD. Its equations have been known since the 1970s, but they have several features that make them devilishly hard to work with. Even today, with the most sophisticated mathematical techniques and the most powerful parallel computers, physicists cannot exactly solve the equations for a nucleon.

The strong force arises when quarks exchange gluons. The process is similar to the generation of the electromagnetic force when electrically charged particles swap photons. But two crucial differences make QCD far more mathematically intractable than electromagnetism. First, photons are electrically neutral and so do not "perceive" other photons directly, but gluons do interact with one another. Second, the strong interaction is about 100 times stronger than electromagnetism (hence its name). With a relatively feeble interaction such as electromagnetism, the simplest processes have the largest effects, and more complicated ones only need to be considered for higher precision. With the strong force, however, very complicated processes involving multiple interactions can make large contributions, and there is no easy way to deal with the resulting mathematics.

In fact, because gluons interact strongly with one another, QCD is a "nonlinear" theory: a small change in conditions can snowball into a large effect. Nonlinear dynamics is central to chaos theory, and the many studies of chaotic systems in recent years have shown how complex they can be. Moreover, QCD is a quantum field theory, implying that virtual quarks and gluons are constantly being created and annihilated; their individually brief but pervasive interactions must be taken into account. And if that were not enough, the uncertainty principle dictates that the quarks, which are confined within the tiny volume of a proton or neutron, must be in motion—at close to the speed of light.

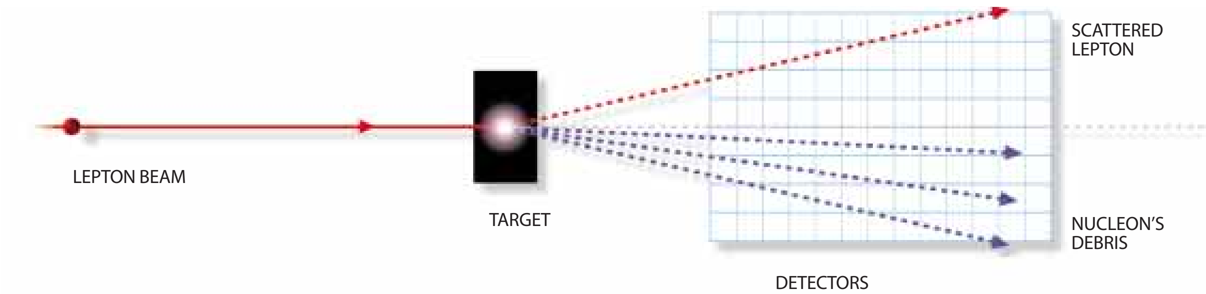
In some respects, spin is more important in QCD than in atomic physics. A hydrogen atom, for example, can have a total spin of zero or one, depending on whether the proton and the electron orbiting it have their spins parallel or antiparallel to each other [*see illustration on this page*]. But the difference in energy of these two alternatives is tiny. In contrast, consider the particle called Δ^+ (delta plus, the sign indicating its electric charge of +1). It is made of the same three quarks as a proton, but the spins add up to 3/2 instead of 1/2. The Δ^+ is 30 percent more massive than a proton, meaning that aligned spins require more energy.

Lepton "Microscopes"

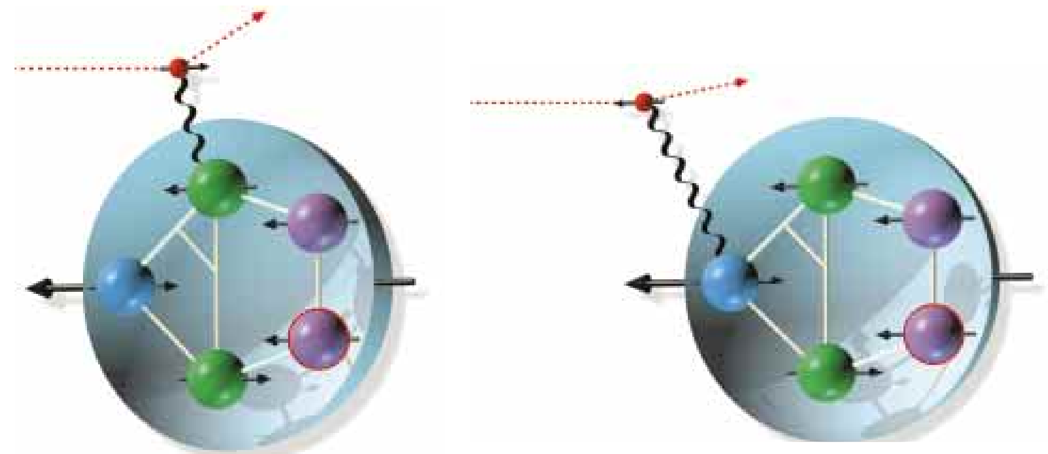
Experimenters investigate the structure of nucleons typically by bombarding a target of them with beams of energetic particles, such as electrons or muons. (The muon is a heavier, unstable cousin of the electron.) These particles, called leptons, are oblivious to the strong

Revealing a Nucleon's Spin Structure

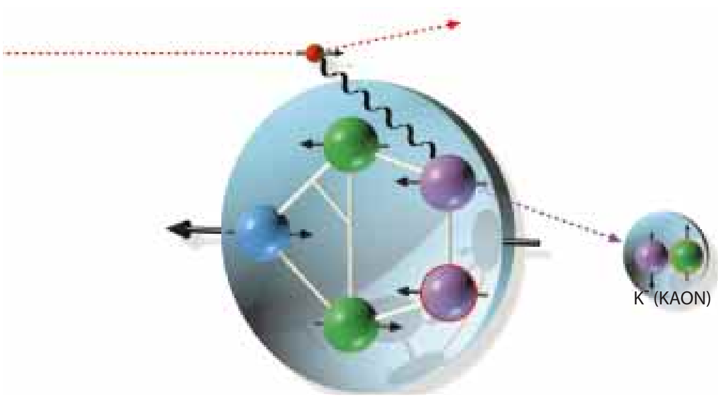
An accelerator directs a beam of polarized electrons or muons ("leptons") at a target of polarized nucleons. Detectors measure the resulting deflections and energy losses of the leptons. Recent experiments also analyze the debris from the nucleons for clues about what type of quark was struck to produce each deflection.



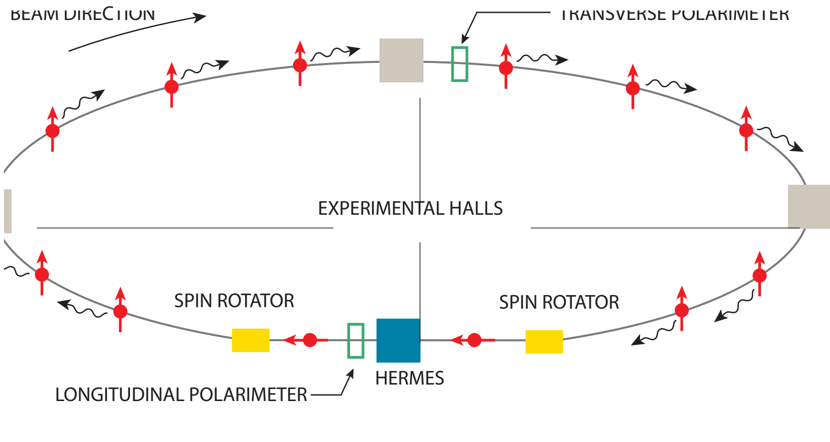
A lepton is deflected when it exchanges a photon with one of the quarks in the nucleon. Leptons with their spins aligned along the beam interact almost exclusively with quarks that have the opposite spin alignment (*below left*). When the beam polarization (or the nucleon polarization) is reversed (*below right*), the leptons interact with different quarks, changing the pattern of scattering angles and energy losses that are seen. The difference reveals the asymmetry of the quark spins in the nucleon.



If a negative kaon is knocked out of the nucleon with large energy (*below left*), the photon probably has struck one of its constituents—a strange quark or an up antiquark. By counting the corresponding lepton deflections, physicists determine the polarization of those quarks. In the HERMES experiment (*photograph*), the electron beam travels in the large gray pipe toward the spectrometer magnet (*blue*). The target and some small detectors are installed in front of the magnet; the main particle detectors are behind the magnet.



SLIM FILMS; HEIKE THUM-SCHMIELAU *DESY* (*photograph*)



LAURIE GRACE

HERA COLLIDER accelerates electrons in a 6.3-kilometer- (3.9-mile-) circumference storage ring. The electrons (*red*) circulate about 47,000 times per second, continuously emitting hard x-rays called synchrotron radiation (*black*). Gradually, over about 30 minutes, the synchrotron radiation polarizes the electron spins (*red arrows*) at right angles to the beam path (100 percent polarization is depicted, but 60 percent is typical in practice). The HERMES target and detectors (*blue*) occupy the eastern experimental hall; three other experiments (*brown*) share the HERA beam. Special magnets (*yellow*) rotate the polarization to lie along the beam path before the HERMES collision point and then rotate it back to transverse afterward. Polarimeters monitor the polarization.

force, so the resulting collisions are governed by electromagnetism. Also, leptons seem to behave like perfect dimensionless points. The mathematics of how they interact with nucleons is thus greatly simplified and very well understood; the complications lie in the structure of the nucleon itself, not in the probe being used.

When an electron or muon passes near a nucleon in the target, it feels a force from the electric charges that make up the nucleon. In the language of quantum field theory, the lepton and the nucleon exchange a photon, transferring energy from one to the other and deflecting the lepton [*see illustration on preceding page*]. By careful measurements of the leptons' deflections and energy losses in the collisions, researchers build up a picture of how electric charges—such as those carried by quarks—are distributed within the nucleon.

The accelerator (which speeds up the leptons) and the detector (which catches the ones deflected from the target) act together like a gigantic microscope. As the momentum of the transferred photon is increased, this microscope examines the nucleon structure in finer detail. Typically a lepton needs an energy of about 100 giga-electron volts (GeV) to resolve details down to a few percent of the nucleon size. (One GeV is the usual energy unit used in QCD physics; it is approximately equivalent to the mass of a proton or a neutron at rest.)

For studies of the spin structure of nucleons, the spins of the particles in both the beam and the target must be polarized—that is, aligned. The basic interaction between the lepton and the target quark is still the exchange of a photon, but if the spin axis of the lepton beam points along the beam, the leptons will primarily exchange photons with quarks having the opposite spin. Thus, from the deflections of the leptons, experimenters learn how quarks with a specific orientation of spin are distributed in the nucleon. In particular, measurements made first with one polarization and then with the beam (or target) polarization reversed reveal the asymmetry of the quark spins—the imbalance of parallel and antiparallel spins.

The first such polarized experiments were carried out in the late 1970s at SLAC with an electron beam and a cryogenic target of butanol (C_4H_9OH). The SLAC results, published in the early 1980s, agreed with expectations that about 60 percent of the proton's spin comes from its quarks and that strange quarks make very little contribution to this. The data were limited, however, by the relatively low energy of the SLAC electron beam (10 to 20 GeV), and the conclusions depended on a plausible extrapolation to higher energies.

In the mid-1980s a group of physicists called the European Muon Collaboration (EMC) began experiments at CERN, the European laboratory for particle physics near Geneva, with a 200-GeV muon beam and a polarized solid ammonia (NH_3) target. A beam of protons from the accelerator first makes a beam of high-energy pions, which decay naturally in flight to muons that are 80 to 90 percent polarized. But the resulting muon beam intensity is only about a millionth of that of the polarized electron beam at SLAC. To cope with this paucity, the EMC's cryogenic targets were made 72 centimeters (28 inches) long. With a shorter target, too few of the muons would interact with a polarized proton while they passed through the ammonia to produce accurate measurements.

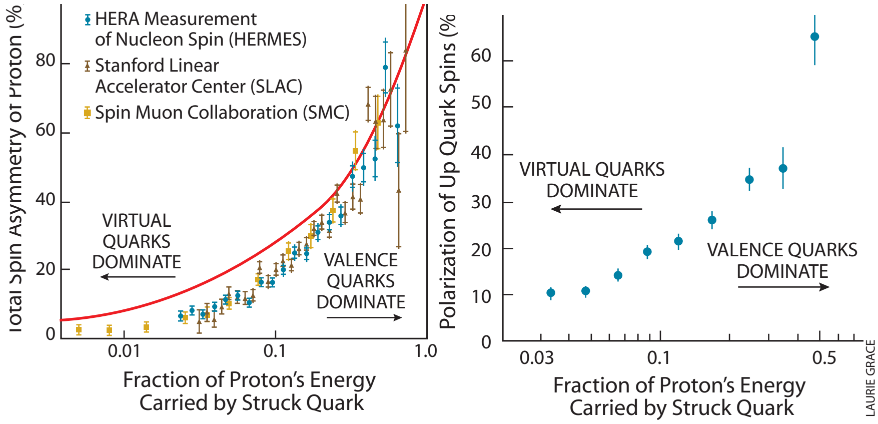
By exploring the proton spin structure at higher energies, the CERN group made the startling discovery that the quark spins contribute very little of the spin of the proton. In addition, it appeared likely that virtual strange quarks within a proton are quite polarized and make an unexpectedly large contribution to the total spin: about 10 percent but aligned the wrong way!

A few years later extraordinary technological advances in achieving highly polarized beams and targets led to a new generation of experiments with much greater precision. As well as technological ingenuity, all involved large-scale organization of manpower and resources. The Spin Muon Collaboration (SMC) took over the earlier apparatus at CERN, substituting a 1.2-meter target (the longest ever built) made with deuterium (hydrogen with a neutron added to the nucleus). New experiments began at SLAC as well, using target materials containing hydrogen or deuterium and also a helium 3 target. Helium 3 has one neutron and two protons with opposite spins that cancel. Experiments with deuterium and helium 3 provide important data on the neutron's spin structure, which should be very closely related to that of the proton.

HERMES and Beyond

In 1988 an international collaboration (including one of us, Rith) proposed adapting for nucleon spin measurements an electron-proton collider called HERA at the German Electron Synchrotron (DESY, pronounced "daisy") in Hamburg. It came to be known as the HERMES (HERa MEasurement of nucleon Spin) collaboration. Electrons circulate around HERA's ring about 47,000 times per second, producing an average beam 10,000 times more intense than the one at SLAC [*see illustration on opposite page*]. This intense beam can be used with low-density gaseous targets of pure atomic hydrogen, deuterium or helium 3. Such targets avoid the spin "dilution" that occurs with targets of butanol and ammonia that have many unpolarized proton and neutron pairs in their carbon, nitrogen and oxygen atoms.

Serious technical concerns had to be overcome. It took four years of effort for the DESY accelerator experts and members of the HERMES collaboration to demonstrate and then routinely attain high polarization. At that point, HERMES received its final approval, and the detectors were built and installed. HERMES began taking data in the summer of 1995.



SPIN POLARIZATION of the proton is measured by many experiments. The total spin asymmetry from recent measurements by SLAC, SMC and HERMES (*left*) shows that quark spins contribute only a small portion of proton spin. Data following the curve would have indicated a larger contribution, as was expected in the early 1980s. The spin polarization of just the up quarks and antiquarks (*right*) was measured recently by HERMES.

The results of all the second-generation experiments agree nicely with one another [*see illustration above, at left*] and confirm that only about 30 percent of a proton's spin is produced by its quark's spins. Moreover, experiments are now beginning to pin down the contribution of each kind of quark by studying the nucleon debris from each collision. The illustration at the right shows recent HERMES results for the polarized up-quark distribution. HERMES will also provide the first *direct* measurements of the strange quark polarizations by singling out those collisions that produce a negative kaon (which consists of a strange quark and an up antiquark).

The missing 70 percent of the spin no longer constitutes a "crisis." It can come from gluon spins (each gluon has a spin of one) and from the orbital angular momentum from the motion of all the quarks and gluons within the nucleon. Indeed, present-day theoretical models of spin structure can match the experimental data provided that the total gluon contribution is about one to two quantum units of spin. An orbital angular momentum (from the motion of all the particles in a nucleon) of about –1 is also required.

That such large quantities are present within a nucleon of total spin of ½ is quite counterintuitive. Can we verify these surprising gluon and orbital contributions independently? At present, no one has proposed a practical way to measure the orbital contribution. Data from HERMES indicate that gluons do contribute to the nucleon's spin, but the extent of the contribution cannot be assessed yet. Studies that collide polarized protons together at high energy should also directly determine the spin from gluons. Such experiments will begin next year at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory [see "A Little Big Bang," by Madhusree Mukerjee; SCIENTIFIC AMERICAN, March]. The next-generation experiment at CERN—COMPASS—will also measure the gluon contribution. If the measured contribution turns out to be too small, we will face a far more drastic "spin crisis" than ever before.

Clarifying the internal structure of the nucleons will also have significance in other realms of particle physics. The spin contributions are intimately related to mathematical structures that appear not only in QCD but also in, for example, weak interactions (which cause some nuclei to decay and help to power the sun). In particular, the Bjorken sum rule, first derived by James Bjorken of SLAC in 1966, relates the scattering of polarized electrons off polarized nucleons (an electromagnetic process) to the decay of a neutron (a weak process).

The spin experiments are verifying the Bjorken sum rule with increasing precision and are thus verifying elements of the basic mathematical structure of QCD and the Standard Model. In this way, scientists are learning more about the fundamental properties of our universe even as they work toward a complete answer to the seemingly simple but remarkably difficult question: What produces the spin of a nucleon?

The Authors

KLAUS RITH and ANDREAS SCHÄFER are both members of the HERMES collaboration. Rith has worked on lepton-nucleon scattering since his 1974 Ph.D., which was on the design and construction of a detector for use with an electron synchrotron at the University of Bonn. He has worked on the muon-nucleon experiments at CERN near Geneva, and he was spokesman for the HERMES collaboration for several years. Rith is a professor of particle physics at the University of Erlangen-Nürnberg in Germany. Schäfer became active in nucleon spin theory during his first postdoc, as a Toleman Prize Fellow at the California Institute of Technology in 1987. The "spin crisis" was just blossoming, and he learned that a group in the same building developing a polarized target "needed a theoretician to help them keep up with the enormous number of theory papers being generated." Schäfer is a professor at the University of Regensburg in Germany, where he leads a high-energy theory and quantum chromodynamics group.

Further Reading

COLLISIONS BETWEEN SPINNING PROTONS. Alan D. Krisch in *Scientific American*, Vol. 257, No. 2, pages 42–50; August 1987.

THE PARTICLE EXPLOSION. F. E. Close, M. Marten and C. Sutton. Oxford University Press, 1987.

WHERE DOES THE PROTON REALLY GET ITS SPIN? Robert L. Jaffe in *Physics Today*, Vol. 48, No. 9, pages 24–30; September 1995.

The Earliest Zoos and Gardens

More than 4,000 years ago rulers in Egypt and Mesopotamia, builders of pyramids and empires, became the first to embark on another pastime: collecting exotic animals and planting ornamental gardens

by Karen Polinger Foster

Few people realize that zoos and decorative gardens have an astonishingly long history. Some 5,000 years ago in the Middle East, writing was invented and the first cities were established. Within 700 years of those momentous events, Egyptian pharaohs had built their famous pyramids, Mesopotamian kings had created the world's first empires, and rulers in both lands had established menageries and botanical gardens.

Over the next two millennia, the zoos grew to include such animals as giraffes, cheetahs and monkeys from Africa, seals from the Mediterranean, and bears and elephants from Asia. The gardens often incorporated groves of rare trees, aviaries of exotic birds and a central pool stocked with unusual fish.

The images on these pages feature some of the best-preserved visual records of the earliest zoos and gardens. The most abundant artistic evidence from Egypt derives from burial sites of about 2500 to 1400 B.C.; the richest evidence from Mesopotamia comes from Assyrian palace reliefs of about 880 to 627 B.C. Throughout the entire period in both areas, ample written records—on clay tablets, papyri, and tomb and palace walls—describe how kings and sometimes other power brokers made zoos and gardens for pleasure and prestige and to satisfy scientific curiosity. Rulers note that they gathered many of their animals, seeds and cuttings from distant lands, frequently setting forth on expeditions for that purpose or receiving their quarry as gifts from fellow leaders or conquered peoples. Proud of their collections, they took pains to ensure that their acquisitions would thrive and reproduce. Indeed, they often employed handlers and gardeners to care for finicky creatures and delicate flora and installed innovative watering devices.

Royal pride is evident, for instance, in a story told through text and painted reliefs in the Theban burial complex of the female pharaoh Hatshepsut. In approximately 1460 B.C., Hatshepsut had the clever idea of procuring myrrh saplings from the Horn of Africa to start a plantation in Egypt. Myrrh, needed for incense and mummification, was very costly to import. "Never was brought the like of this," she proclaimed, "for any king who has been since the beginning." While she was at it, Hatshepsut also picked up some baboons for the royal menagerie. Other texts note that her successor, Tuthmosis III, delighted in a zoo that featured four Indian birds "that laid eggs daily," the first domestic chickens in Egypt.

During the ninth century B.C., a Mesopotamian king—Ashurnasirpal II of Assyria—boasted, "I collected herds and brought forth their increase. From lands I traveled and hills I traversed, the trees and seeds I noticed and collected." And a sixth century B.C. hymn from southern Mesopotamia speaks of exotic floral wonders that "enhanced the pride of the city."

In the sixth to fourth centuries B.C., the vast Persian Empire absorbed Egypt and Mesopotamia as provinces. Persian leaders continued to collect foreign fauna and flora but conceived a new, more formal garden plan. The Persian garden, rectangular and enclosed by high walls, was usually subdivided into four equal sections by canals that intersected at a small pool. These elaborate pleasure gardens were called *pairi-daēza* ("wall-surrounded"), a term the Greeks rendered as *paradeisos*. Over the next 1,000 years, "paradise" became a fundamental concept in Christian and Islamic thought. The ancient Egyptian and Mesopotamian garden evolved into the Eden of the Bible and the Koran, a reflection on earth of the splendors promised in heaven.

BRITISH MUSEUM

ELEGANT GARDEN AND POOL graced the estate of an Egyptian official, possibly named Nebamum, in about 1400 B.C., according to this painting found in his now lost Theban tomb. The pool evidently housed ducks, geese and fish that swam among lotuses. Borders of papyri, poppies and other flowering plants edged the pool. Two varieties of sycamore fig trees, three kinds of palms (date, doum and argun) and luxuriant vines provided welcome shade, and occasional mandrakes bore masses of fruit. The woman emerging from a tree at the upper right and presiding over a table laden with food and drink is the goddess of the sycamore.

In keeping with Egyptian artistic conventions, the painter combined several perspectives to convey as much information as possible. An aerial view best illustrates the layout of the garden and the shape of the pool; a side view reveals more of the plants and animals. So as not to block the pool, the trees and bushes grow outward in three directions. Many artists of the time would have also drawn the bottom rows upside down, but this gifted artist chose a more naturalistic, upright stance.

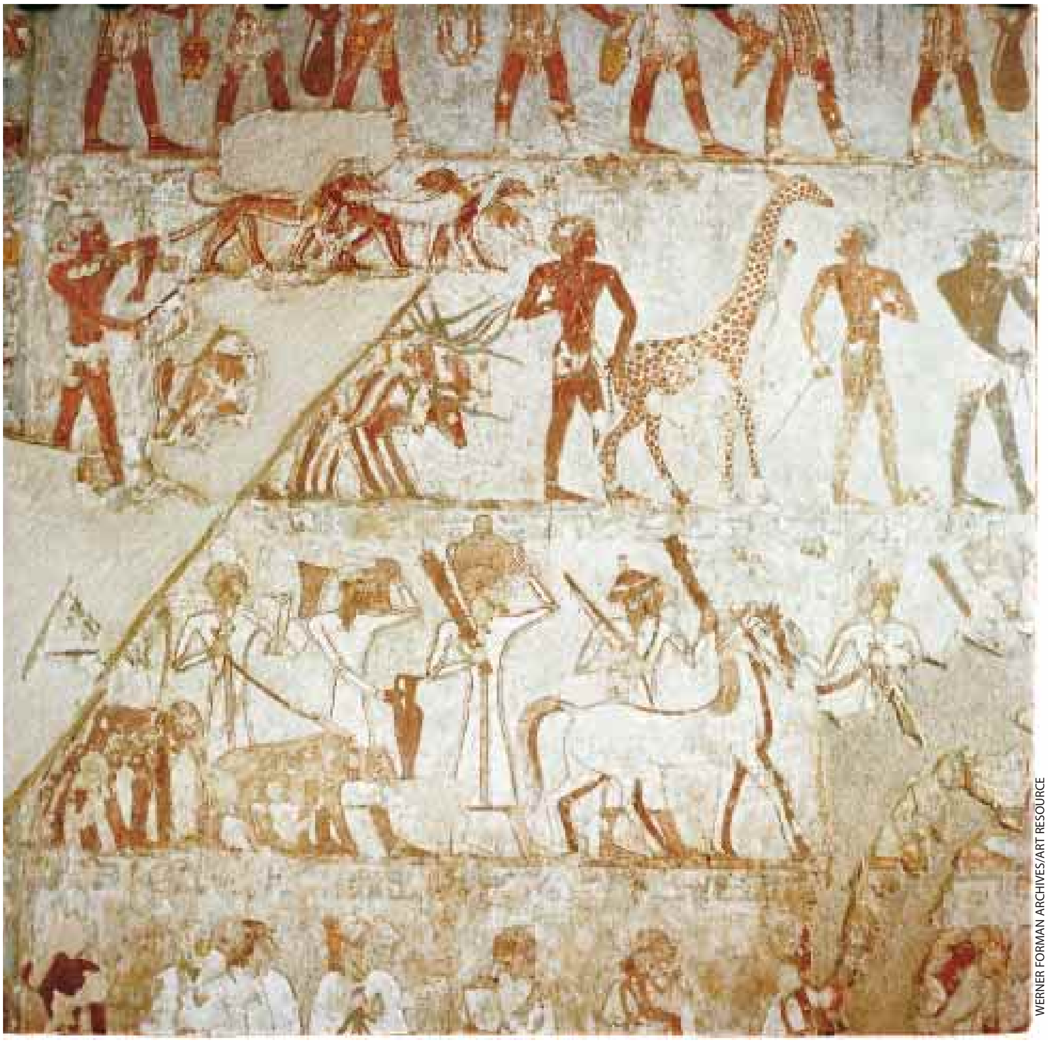
ÄGYPTISCHES MUSEUM, BERLIN; PHOTOGRAPH BY JÜRGEN LIEPE

FRAGMENT OF A PAINTED RELIEF is the oldest pictorial evidence that royalty in the ancient Middle East collected exotic animals. It reveals that Syrian bears, fitted with collars and leashes, were among the prizes gathered for the Egyptian pharaoh Sahure (who ruled from 2458 to 2446 B.C.) during a trading expedition to the Levant, along the eastern coast of the Mediterranean. The fragment, from the king's pyramid complex at Abusir, is part of a visual tale that adorned Sahure's mortuary temple, a standard pharaonic burial structure used for celebrating the cult of a dead king. Reliefs along the north wall present the travelers sailing up to the Levant; those with the bears, on the opposite wall, tell of the return trip. Where the royal menagerie was located and whether any of the bears were trained to perform remain uncertain.

The artist must have seen the animals firsthand, for their long claws, lumbering gait and bemused expressions are strikingly naturalistic. The traders also imported tall, single-handled Syrian vessels (including the one at the bottom left) filled with Levantine products, as well as massive cedar logs, which were much valued in Egypt.

MODEL GARDEN IN A BOX, the only Egyptian garden diorama known, was found in the Theban tomb of Meket-Re, a high-ranking Egyptian official of about 2010 B.C. Sycamore fig trees (made of wood and bearing individually attached leaves) surround a rectangular copper-lined basin that must once have held water. At the rear is a veranda supported by brightly painted wooden columns of a design inspired by bundled stalks of lotus and papyrus. Three small drain spouts extend from the veranda roof.

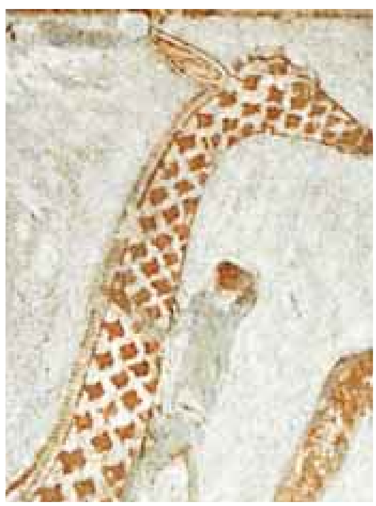
From about 2500 to 1900 B.C., wooden models supplemented tomb wall decorations chronicling aspects of daily life. Many were boxes, presenting walled, interior views of various enterprises, such as granaries and slaughterhouses. Others were freestanding—among them miniature boats with cloth sails spread and nets filled with tiny wooden fish. Although Meket-Re's garden contains no people, most models are populated by wooden workers busy at their tasks.



WERNER FORMAN ARCHIVES/ART RESOURCE

EXOTIC ANIMALS parade across a wall painting in the Theban tomb of Rekhmire, a high official who served in the late 15th century B.C. under successive Egyptian kings: Tuthmosis III and Amenhotep II. During their reigns, regular military and commercial expeditions expanded Egypt's imperial sphere southward into Nubia and northward into the Levant, and animals from both frontiers can be seen in the painting. Near the top, Nubians lead hunting dogs, long-horned cattle and a young giraffe with a green monkey clinging to its neck. Toward the bottom, Syrians enter with an elephant, a bear and horses, as well as with copper ingots, elephant tusks and assorted containers.

The rendering of the giraffe is particularly striking. Close inspection reveals that the animal's markings are small quatrefoils (*detail*). By this subtle geometric alteration, the artist makes a political point: just as this strange beast from Africa now conforms to familiar Egyptian patterns, the Nubians have been forced to submit to Egyptian domination.



LEASHED MONKEYS arrived at the Assyrian court (in Mesopotamia) of Ashurnasirpal II with a host of other animals, including elephants, bears, rare deer and Mediterranean "sea creatures" (probably dolphins, seals and the like). In 879 B.C., the king established a new palace and administrative center at Nimrud. Soon after, he began to escalate his acquisition of exotic fauna. These figures belong to throne room reliefs that display foreigners presenting luxury goods to the court; the scrimlike text running horizontally is a standard inscription in praise of the king. The site is known to have contained enclosures for the animals as well as extensive gardens and parklands, but no traces of those pens or gardens have been found.

Stylistically, Ashurnasirpal's reliefs display careful composition and juxtapositions of shape and pattern. The tail of the lower monkey, for example, skims his handler's foot, leaving visible the pointed toe of the shoe. The animals' stippled coats contrast with the striated fringes of their handlers' garments. The artist has also allotted enough free space for an unencumbered view of the lower monkey's head and forepaws, which, interestingly, have a decidedly human aspect.

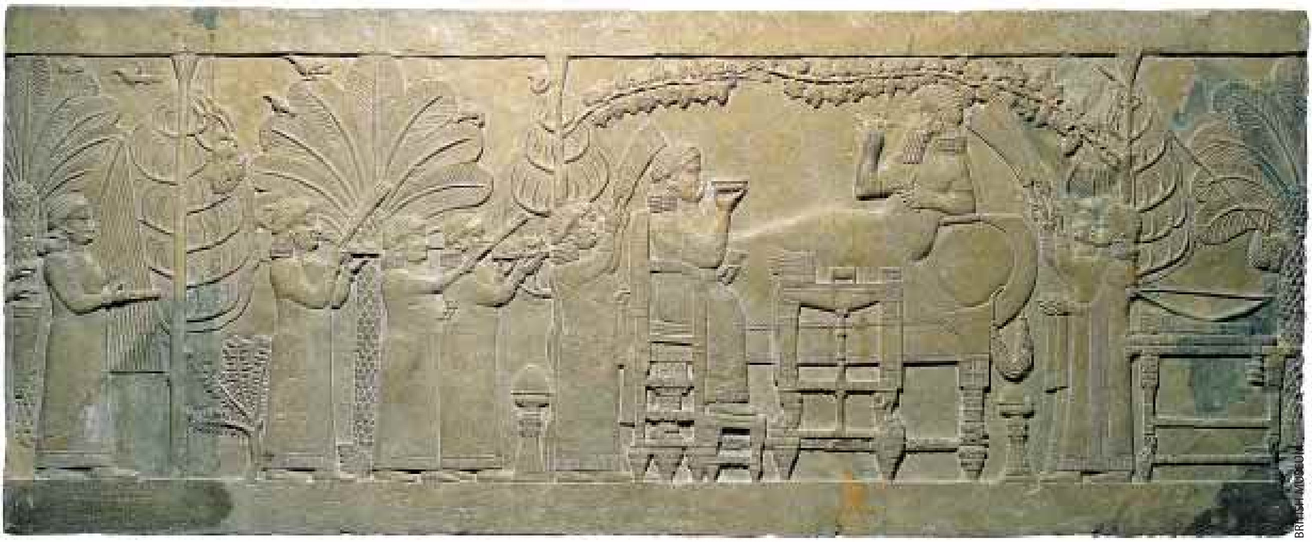
BRITISH MUSEUM

BLACK OBELISK, from the palace at Nimrud of Shalmaneser III, recounts—in 20 relief panels and in text along the top and bottom borders—the king's many military campaigns and the tribute he received from all corners of his empire during his reign (858 to 824 B.C.). The side visible at left highlights creatures brought to the king from the East: a pair of "camels whose backs are doubled," an Indian elephant and two apes. A change in artistic style is evident in the obelisk: the figures rendered during the reign of Shalmaneser III exhibit more sculptural features than do the earlier, relatively linear reliefs of Ashurnasirpal II.

BRITISH MUSEUM

ANIMAL PARK above was designed with great care by the Assyrian king Sennacherib at what he called his "Palace without Rival," established at Nineveh in about 700 B.C. Sennacherib was particularly interested in creating natural habitats for breeding foreign and indigenous creatures. Texts assert that "the plantations were most successful; the herons which came from far away nested, and the pigs and others produced young in great numbers." This relief includes a prolific sow, strolling with her piglets near the center left. Above, deer are nearly hidden among the interlaced reeds.

The king lavished equal attention on his elaborate gardens (*not shown*). Indeed, a recent study by Stephanie Dalley of the University of Oxford suggests that the legendary Hanging Gardens, rather than being the handiwork of the sixth century B.C. Babylonian ruler Nebuchadnezzer, were in fact the renowned gardens of Sennacherib, many miles to the north.



BRITISH MUSEUM

GARDEN PARTY recalled in this relief was held by Sennacherib's grandson Ashurbanipal, who ruled until 627 B.C. Ashurbanipal preserved Sennacherib's creations and also maintained his own gardens and zoos. The relief, from his North Palace at Nineveh, pictures Ashurbanipal celebrating a victory over Elam, a kingdom to the southeast. He is reclining on an inlaid couch, one elbow propped on a cushion, and raising his drinking cup to his queen. Attendants fan the royal couple, bring them refreshment, and play harps and other instruments. The entire scene would appear a bucolic delight but for one gruesome detail: the severed head of the Elamite king hangs (upside down) from a ring on a tree at the left (between two palms). Its unpleasant odor may explain why Ashurbanipal and his queen hold jasmine bouquets and have a pair of incense burners nearby.

Unknown to Ashurbanipal, Nineveh's days were numbered. In 612 B.C. its eastern enemies, the Medes, sacked the capital, putting an end to the Assyrian empire. Its zoos and gardens, the pride of generations of Assyrian kings, fell into ruins.

The Author

KAREN POLINGER FOSTER, who holds a doctorate in Near Eastern languages and civilizations from Yale University, is a visiting faculty member at Yale and is writing her third scholarly book, *Gardens of Eden: Exotic Flora and Fauna in Mesopotamia, Egypt, and the Aegean.* She has also completed a children's book—*The City of Rainbows: A Tale from Ancient Sumer*—just published by the University of Pennsylvania Museum of Archaeology and Anthropology.

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THE FUTURE OF

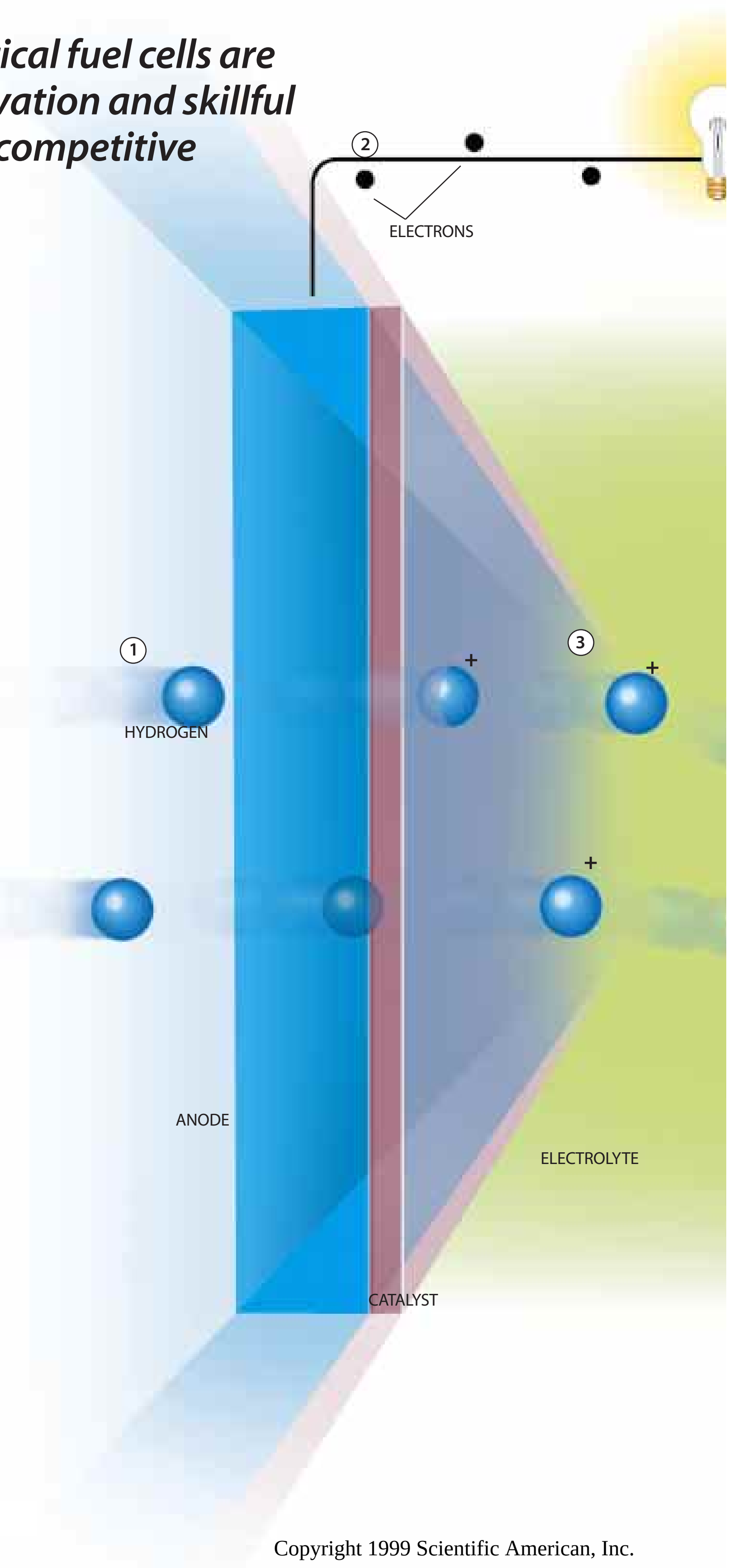
The obstacles to building practical fuel cells are numerous, but continued innovation and skillful engineering could make them competitive

In 1839 William R. Grove, a British physicist, demonstrated that the electrochemical union of hydrogen and oxygen generates electricity. Fuel cells based on this concept, however, remained little more than laboratory curiosities for more than a century, until the 1960s, when the National Aeronautics and Space Administration began deploying lightweight—and expensive—versions of the devices as power sources for spacecraft. Today the technology, which promises clean, efficient and quiet operation, is being touted for a host of applications, including cellular phones, laptop computers, automobiles and home power supplies.

But numerous hurdles loom. For starters, there is the question of fuel source. Liquid hydrogen, an energy-rich substance, must be stored at impractically low temperatures just above absolute zero. Methanol, a liquid at room temperature, contains abundant hydrogen, but extracting it usually entails reformation, a cumbersome chemical conversion. Furthermore, pricey platinum catalysts are often required. These and other factors complicate the basic design of fuel cells, often necessitating the addition of elaborate subsystems.

Undaunted, various research groups around the world have been aggressively refining the technology toward practicality. Such efforts have, for instance, slashed the platinum requirements for one type of fuel cell by more than a factor of 30. In the following special report, experts in the field describe the current state of fuel-cell commercialization in three areas: vehicles, where the internal-combustion engine remains difficult to beat; stationary applications, where interest has shifted from megawatt systems for electric utilities to smaller devices targeted for home use; and portable electronics, where miniature fuel cells could replace rechargeable batteries.

—The Editors



FUEL CELLS

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FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS

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DAIMLER-BENZ

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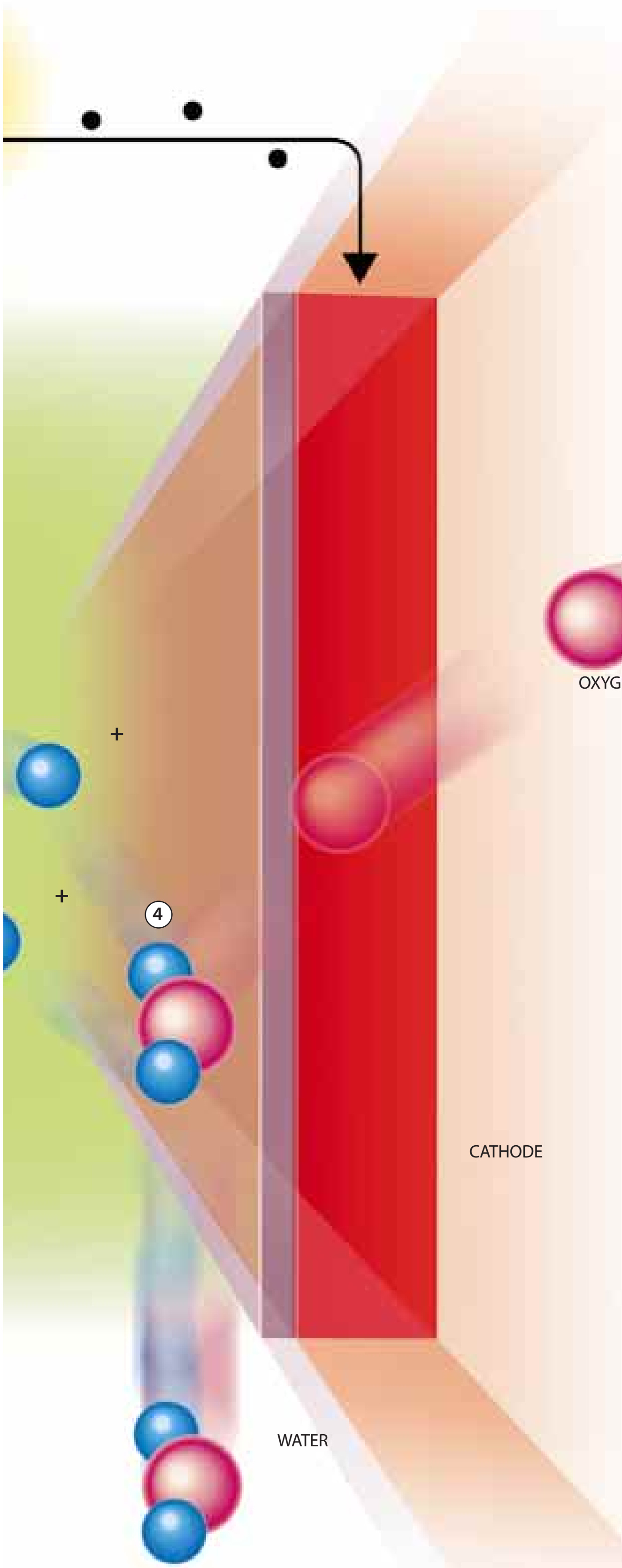
PLUG POWER



GEORGE RETSECK

FUEL CELL is basically a simple device, consisting of two electrodes (an anode and cathode) that sandwich an electrolyte (a specialized polymer or other material that allows ions to pass but blocks electrons). A fuel containing hydrogen flows to the anode (*1*), where the hydrogen electrons are freed, leaving positively charged ions. The electrons travel through an external circuit (*2*) while the ions diffuse through the electrolyte (*3*). At the cathode (*4*), the electrons combine with the hydrogen ions and oxygen to form water, a by-product. To speed the reaction, a catalyst such as platinum is frequently used. Fuel cells and batteries are similar in that both rely on electrochemistry, but the reactants in a fuel cell are the hydrogen fuel and oxidizer, whereas in a battery they are the materials (for example, nickel oxyhydroxide and cadmium) used in the electrodes.

The Electrochemical Engine for Vehicles

Fuel cells can power cleaner buses and cars, but key engineering and economic obstacles will delay widespread adoption of the technology

by A. John Appleby

As the number of cars, trucks and buses on the road increases, the need for alternatives to the internal-combustion engine becomes ever more apparent. The largest of the world's oil reserves are in the politically unstable Middle East and in any event cannot last indefinitely. The health hazards posed by nitrogen oxides and other compounds in vehicle exhausts are well known, and concerns about emissions of the greenhouse gas carbon dioxide are also growing. Although cars are becoming cleaner and more efficient, the gains are being offset by the rapid growth in the total number of vehicles, especially in Asian markets. In 1996 some 634 million vehicles were on the road worldwide, an increase of almost 30 percent from the figure a decade earlier; collectively, they emitted some 3.7 billion tons of carbon dioxide, according to the International Energy Agency.

Automakers are investigating a variety of ways to reduce emissions drastically. Electrochemical fuel cells producing power for electric drive motors are now widely seen as a promising possibility. Unlike familiar dry cell batteries, which store a fixed amount of energy in their electrodes, fuel cells can run as long as fuel and oxidant are supplied—or at least until components in the cells degrade.

Most major manufacturers now have programs for producing fuel cells for autos, and recent demonstrations have caught the public eye. DaimlerChrysler and General Motors both say they will make some passenger cars for the mass market by 2004; the London-based company Zevco is planning to build fuel cells for commercial vehicles in New York.

Although fuel-cell-powered vehicles have only recently emerged into the public spotlight, the use of fuel cells for traction actually goes back to the 1950s. And they have supplied power in all manned space missions since Project Gemini in 1965.

Chemical Choices

Vehicle fuel cells may employ various chemicals as their electrolyte, the material that electrically connects the electrodes inside the cell. Hydrogen supplied to the anode (the negative terminal, in this context) reacts there, liberating electrons. The resulting current flows through an external circuit to the cathode (the positive terminal), where electrons combine with oxygen. Ions flow through the electrolyte to complete the circuit. The only waste product is water. Fuels other than hydrogen can be used in principle, but then products from the reaction "poison" the catalyst, reducing output voltage and efficiency. Fuel cells that run at temperatures low enough for mobile use rely on a catalyst, generally platinum, to speed reactions to practical rates.

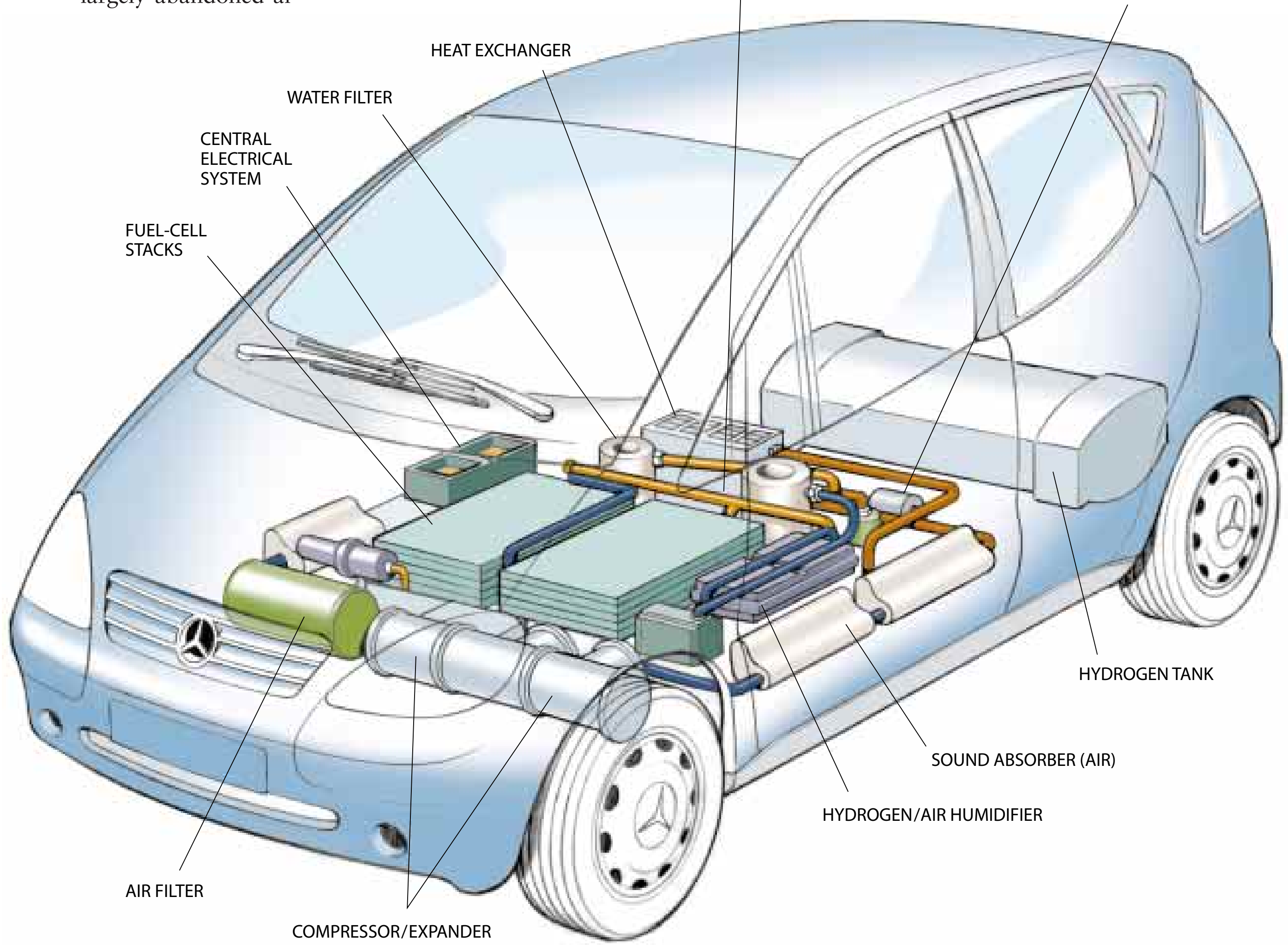
The direct chemical-to-electrical energy conversion accomplished in a fuel cell can theoretically reach a very high efficiency. In practice, the slow re-

MODERN FUEL-CELL-POWERED CAR, DaimlerChrysler's Necar 4, uses fuel cells mounted under the floor to generate electricity. A compressor maintains them at pressure. Air and hydrogen fuel are conditioned by a humidifier and a heat exchanger; a condenser captures wastewater. Liquid-hydrogen fuel is stored in a cryogenic tank. An air-cooled radiator (*not shown*) eliminates waste heat.

action of oxygen at the cathode limits the achievable efficiency to 45 to 60 percent, even using the best platinum or platinum-alloy catalysts. But this is still better than the internal-combustion engines of today's autos, which might reach 35 percent efficiency under ideal conditions but actually average about 15 percent. One reason for the superior performance of fuel cells is that they do not have to idle when a vehicle is stationary.

Other significant efficiency losses of fuel cells result from the electrical resistance of the electrolyte and from variations in its concentration from one microscopic site to another. These losses are minimized by employing strongly acidic or alkaline electrolytes. Alkaline fuel cells operating on compressed hydrogen and oxygen were the first type to power a vehicle, an Allis-Chalmers farm tractor, in 1959. Their disadvantage has been that they need to be supplied with hydrogen that contains no contaminating carbon dioxide, or it will react with the electrolyte to form a solid carbonate. Because many automotive concepts involve generating hydrogen on board from other fuels—a process that produces some carbon dioxide—the major technology developers have largely abandoned alkaline fuel cells, although they have great promise where hydrogen of industrial purity is available. They can be made from inexpensive materials, and engineers learned in the 1980s how to make carbonate-insensitive cathodes, which lessen the susceptibility to carbon dioxide. Furthermore, alkaline cells can function with much less platinum than acid-based fuel cells can.

Acidic electrolytes are insensitive to carbon dioxide but have their own limitations. Typical acids require liquid water to conduct hydrogen ions, so cells must then operate below the boiling point of water. That requirement constrains efficiency. Concentrated phosphoric acid is an exception, however, and cells using it can operate at 200 degrees Celsius (390 degrees Fahrenheit). Some hospitals and hotels have used phosphoric acid cells operating on ambient air and hydrogen-rich fuel generated from natural gas since the early 1990s. Similar cells have also been used to power city buses, but the several-hour warm-up period that this type needs makes its use in consumer vehicles unlikely.



GEORGE RETSECK SOURCE: DAIMLERCHRYSLER

Because most aqueous acids are either volatile or unstable, chemists started to experiment in the 1960s with synthetic polymers as electrolytes. Modern versions, such as Du Pont's Nafion, contain sulfonic acid groups that allow protons to flow readily through them. The material is formed into a membrane that separates the electrodes. This design, the proton-exchange membrane fuel cell, runs at about 80 degrees C and is now seen as the leading technology for use in cars. Most recent fuel-cell demonstrators have employed this type.

Proton-exchange membrane fuel cells depend on platinum as their catalyst. Typically particles of the metal about 10 atoms in diameter—the smallest achievable size—are deposited on the surface of fine particles of carbon. Platinum's high cost has always been a major factor holding back commercial development of these devices. In 1986 the amount needed was about 16 grams per kilowatt of power produced (a kilowatt is equivalent to 1.3 horsepower). The 16 grams (0.6 ounce) would cost $180 at today's prices, far too much for the mass market. An automobile needs to produce 50 kilowatts to accelerate, although a hybrid design could get by with a fuel cell providing perhaps 15 kilowatts and a battery to help out during periods of peak power demand.

Precious Platinum

Investigators at Los Alamos National Laboratory and at the research center that I direct at Texas A&M University made strides toward reducing the amount of platinum needed in proton-exchange membrane cells in the late 1980s and early 1990s, and more recently some commercial companies have made important contributions. The quantity typically used in modern cells corresponds to $6 to $8 per kilowatt—a 30-fold improvement since 1986. Further improvements in the structure of electrodes and in the way platinum is used might reduce the amount of the metal needed by about half but barring unforeseen breakthroughs probably not more. Researchers have yet to find a substitute for platinum at either electrode.

The membrane-electrode assembly of a modern cell is as little as 2.5 millimeters (0.1 inch) thick. The cathode of one cell and the anode of an adjacent one are physically separated by a plate that connects them electrically in series. On each side of this plate are either gas distribution channels or porous materials that allow hydrogen and oxygen to reach the electrodes easily. The plates may also contain channels for circulating cooling water.

To make a practical power source, a series of assemblies and plates are bolted together in a "stack." In 1989 Ballard Power Systems in Vancouver, B.C., developed a 45-kilogram stack with a volume of about 30 liters (7.9 gallons) that produced five kilowatts of power from stored hydrogen gas and pressurized air. Though impressive, the design still had impractically high platinum loadings, corresponding to about $80 per kilowatt. In 1995 Ballard announced a much improved stack that could compete in performance with the internal-combustion engine. This design had the same weight and volume but generated 32.3 kilowatts and achieved an efficiency of 54 percent. Various generations of Ballard's stacks are now powering buses in Vancouver and Chicago as well as several experimental DaimlerChrysler vehicles.

Automobiles demand higher performance than buses do. But U.S. automakers cooperating in a federal initiative, the Partnership for a New Generation of Vehicles, have selected proton-exchange membrane fuel cells as one of two promising technologies that could help achieve the project's goal of developing an ultralow-emission passenger car. (The other is a hybrid concept that employs a high-efficiency internal-combustion engine coupled with batteries.) Received wisdom in the auto world is that an "electrochemical engine"—a fuel-cell stack powering electric motors—could compete economically with an internal-combustion engine if the cost could be brought down to $50 per kilowatt.

That might be possible in time. There are two competing approaches. One, as indicated above, is to combine a fuel cell with a battery that would provide supplementary power when necessary. This combination makes it possible to employ regenerative braking: when the vehicle is slowing down, the traction motors serve as brakes that generate power to recharge the battery. The battery can also provide power at start-up if the vehicle has a hydrogen-production system that needs time to warm up. Such a system can achieve an overall efficiency of about 40 percent. It has been used in several vehicles, including buses powered by experimental phosphoric-acid fuel cells.


KARL KORDESCH

AUSTIN A40 SEDAN was equipped with Union Carbide alkaline fuel cells in 1966 by Karl Kordesch. Though historically important, the vehicle was hardly practical: the cells occupied much of the interior of the passenger compartment. Tanks of compressed hydrogen are visible on the roof.

The other approach is to use an electrochemical engine with no supplementary battery and no regenerative braking. Ballard followed this strategy in its buses powered by proton-exchange membrane fuel cells. This approach can reach 50 percent efficiency with an average load. But because the fuel cell must be more powerful, it is more expensive. Furthermore, the world supply of platinum is limited, and the metal is in demand for many other applications. If two million cars with 50-kilowatt electrochemical engines were made every year—about 5 percent of current auto production—they would use 50 metric tons of platinum, about one third of the current global production of the metal. This consideration suggests that pure proton-exchange membrane fuel-cell vehicles will not dominate the future world market. Hybrid vehicles combining a battery and a smaller fuel cell could be made in much larger numbers, especially if the fuel cell were alkaline, because this type needs only one fifth as much platinum as proton-exchange membrane models. Zevco is pursuing this option.

Achieving Peak Performance

A July 1998 report to the California Air Resources Board estimated that carmakers will have spent $1 billion to $1.5 billion on the proton-exchange membrane fuel cell by July 2000. Yet to achieve widespread acceptance in coming years, a fuel-cell vehicle must have clear economic advantages over hybrid internal-combustion engine/battery systems that are likely to be developed: merely having negligible emissions is not enough.

In an effort to boost efficiency and thereby help the economics, developers have experimented with pressurizing cells to a few atmospheres, which increases the rate at which hydrogen and oxygen diffuse and react. This maneuver can reduce the amount of platinum needed, although the gains are modest and the heavier containment necessary to operate at pressure adds to a stack's weight. Moreover, efficient operation requires oxygen to be supplied in excess of requirements, so the amount of air that has to be compressed is much more than the amount consumed. Because compressors are noisy and inefficient, pressurization is, all in all, of questionable value.

Ballard appears committed to the idea, however, which enables the company to exploit the high pressure in its cells to expel water that tends to clog the cathode gas channels. In contrast, International Fuel Cells in South Windsor, Conn., a venture of United Technologies and Toshiba, has shown that unpressurized operation can lead to a more efficient and lighter cell. It utilizes permeable graphite containing microscopic pores to control water movement. Manufacturers have successfully tested the tolerance of membrane electrode assemblies for being frozen and thawed down to −40 degrees C, although the pure water used for cooling and keeping the membrane moist must be drained out first.

To reduce costs, manufacturers are looking at using lighter-weight molded graphite-polymer composites and corrosion-resistant metal foams in the plates connecting electrodes. The cost of membranes, $95 per kilowatt in a typical atmospheric-pressure stack, is still a significant obstacle. Du Pont states that prices should fall almost 10-fold if it can sell enough for 250,000 autos a year. That is still likely to be too expensive, so developers are looking at different electrolyte chemistries, though with no notable success to date.

If fuel cells are ever to be widely used in vehicles, improvements will also be needed in the onboard systems for either storing hydrogen or manufacturing it. If the gas is to be delivered to vehicles in its elemental form, an entirely new network of hydrogen refueling stations would have to be established.

It is easy to make hydrogen from natural gas. Hydrogen with an energy content equal to a gallon of gasoline might cost $1.20 to $1.50, which—because a fuel-cell vehicle can operate more than twice as efficiently as today's autos—could provide very low fuel costs per kilometer. More challenging are the systems that would be required for a car to carry three kilograms of hydrogen, the amount necessary to drive a small car 500 kilometers. Three kilograms may not sound like very much, but at atmospheric pressure it would occupy 36,000 liters—the volume of several entire cars.

A pressure vessel could carry compressed hydrogen gas, but it would occupy 180 liters, a lot of space in a car. Some designs proposed by Ford, which incorporate advanced composite materials, might, however, weigh only 25 kilograms.

An alternative would be to develop a nationwide liquid-hydrogen delivery system. A cryogenic vessel storing three kilograms would weigh 45 kilograms and occupy 100 liters, more than a gasoline fuel tank but manageable. Yet liquefaction wastes 30 percent of the energy of the fuel, and liquid hydro-

BALLARD POWER SYSTEMS

OPERATIONAL BUS built by Ballard Power Systems in Vancouver, B.C., is powered by proton-exchange membrane fuel cells (*visible at right*). The bus carries compressed hydrogen fuel and emits no pollutants.

KEY DEMONSTRATIONS OF FUEL-CELL-POWERED VEHICLES

Date	Developer	Vehicle	Technology	Fuel, Range (where available)
1966	Karl Kordesch	Austin A40 sedan	6 kilowatts, Union Carbide, alkaline*	Compressed hydrogen, 320 km
1990 (*Operational April '94*)	H Power, Georgetown University, U.S. government	Three 9.1-meter buses	50 kW, Fuji Electric, phosphoric acid*	Reformed methanol supplies hydrogen
1991 (*Operational Feb. '93*)	Ballard Power Systems	9.8-meter bus	120 kW, Ballard Mk 5, p/proton-exchange membrane	CH
Oct. 1993	Energy Partners	"Green Car" sports car	15 kW, p/PEM	CH, 100 km
April 1994	Daimler-Benz	Necar (Mercedes-Benz 180 goods van)	60 kW, Ballard Mk 5, p/PEM	CH
May 1996	Daimler-Benz	Necar 2 (V-class Mercedes-Benz minivan)	50 kW net, Ballard Mk 7, p/PEM	CH, 250 km
Sept. 1997	Daimler-Benz	Necar 3 (Mercedes-Benz A-class subcompact)	(as above)	RM, 400 km
July 1998	DaimlerChrysler	Necar 4 (as above)	(as above)	Liquid hydrogen, 400 km
1994–97	Ballard	Six 12.2-meter buses	205 kW net, Ballard Mk 6, p/PEM	CH
Nov. 1996	Toyota	RAV4 sport-utility	10 kW, p/PEM*	Metal hydride stores hydrogen, 250 km
Sept. 1997	Toyota	RAV4 sport-utility	25 kW, p/PEM*	RM, 500 km
May 1997	Daimler-Benz	Nebus 12-meter O405 N bus	190 kW net, Ballard, p/PEM	CH, 250 km
Aug. 1997	Renault	Laguna station wagon	30 kW, De Nora (Milan), p/PEM	LH, 500 km
Dec. 1997	Mazda	Demio FCEV station wagon	25 kW, p/PEM*	MH, 170 km
May 1998	Georgetown University, Nova BUS, U.S. Department of Transportation	12-meter bus	100 kW net, International Fuel Cells, phosphoric acid*	RM, 550 km
July 1998	Zevco	Millennium London taxi	5 kW, alkaline*	CH, 150 km
Oct. 1998	General Motors (Opel)	Zafira minivan	50 kW, p/PEM*	RM

*Hybrid system including battery or other storage device; p/ = pressurized

RICHARD HUNT

NUMEROUS FUEL-CELL-POWERED VEHICLES based on various engineering strategies have been built in recent years. The table shows some of the more notable vehicles licensed for use on the highway, including some buses now in service. Many other projects are in progress.

gen has a high boil-off rate; you might return to your car after leaving it at the airport for a week to find all the fuel had boiled away. Moreover, accumulations of hydrogen gas pose a risk of explosion.

Another option is to combine hydrogen with alloys of compounds called metal hydrides, which can reversibly store up to 2 percent of the gas by weight. These materials are expensive and heavy but compact: they could pack the required three kilograms into a reasonable volume of 50 liters. Researchers at Northeastern University announced last year a storage method that involves reversibly absorbing hydrogen inside carbon nanofibers at ambient temperature. Their results require confirmation, but if the amount stored is within a factor of two of the amount claimed, this technique could reduce the volume needed to hold three kilograms of hydrogen dramatically—to 35 liters.

Fill 'Er Up

Rather than building cars that require hydrogen fuel, automakers might opt instead to design vehicles that make hydrogen on board from a carrier fuel, such as methanol or even gasoline. Cars with such processing systems will be ultralow-emission, not zero-emission, vehicles because onboard processors will inevitably create some pollutants. DaimlerChrysler and General Motors agree that a methanol-based fuel system is the best technical alternative to hydrogen. But like hydrogen, methanol would require expensive new tanks and pumps at service stations. The onboard "reforming" to make hydrogen from methanol is accomplished by reacting it with steam at 280 degrees C in the presence of a catalyst. Phosphoric-acid fuel cells work particularly well with a methanol reformer because their relatively high operating temperature allows them to supply "free" steam for the conversion. The elevated temperature also makes them resistant to poisoning by small amounts of carbon monoxide produced as a contaminant.

For typical phosphoric-acid cells, a respectable methanol-to-electricity efficiency of approximately 50 percent is possible. During the 1990s, H Power in Belleville, N.J., developed several experimental buses of this type. They ran quietly and were twice as efficient as diesel buses, yet they emitted only 1.5 percent of the carbon monoxide and 0.25 percent of the nitrogen oxides allowed by federal law.

Methanol reforming is less easily combined with a proton-exchange membrane fuel cell because a catalytic conversion step is needed to reduce levels of carbon monoxide in the product, and even so the fuel cell needs a lot of platinum-ruthenium alloy catalyst at the anode to prevent poisoning. In addition, some of the hydrogen produced in the process has to be burned to produce steam for the reformer. A system built by Toyota achieved an average overall efficiency of only 37 percent. Some would question whether this is a goal worth pursuing, because that level of efficiency can be achieved by a hybrid internal-combustion engine, and methanol costs about twice what gasoline does for the same energy content. Moreover, a methanol reformer is large and heavy.

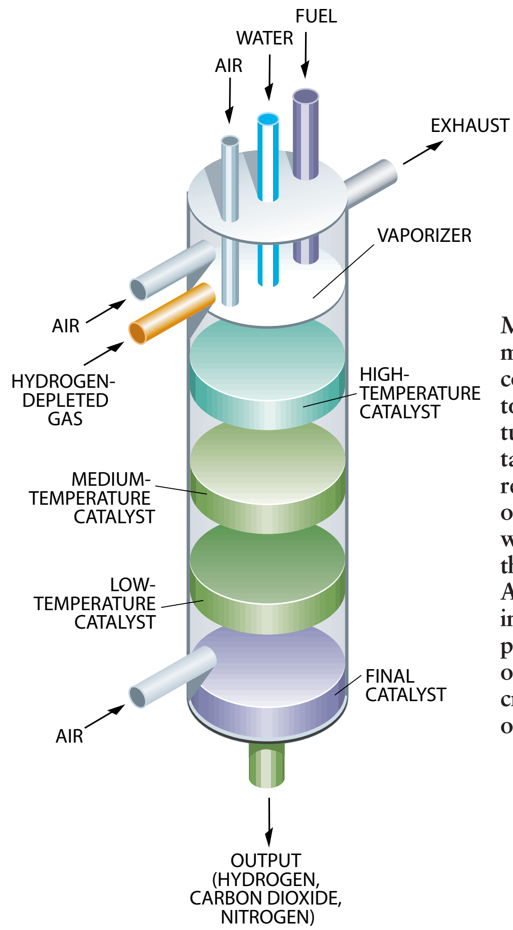
DaimlerChrysler and Shell are considering gasoline itself as a fuel-cell feedstock because it would make use of the existing $200-billion gasoline distribution system. Vehicles would carry a multifuel steam processor that could make hydrogen from methanol or gasoline, burning some of the fuel to provide the steam required. A two-stage process would be needed to clean up the hydrogen. Argonne National Laboratory has tested a system that can convert pump gasoline to hydrogen with an efficiency of 78 percent. Yet after factoring in fair allowances for the energy needed to generate steam and the efficiency of the fuel cell, the efficiency of a vehicle using this system with gasoline would be an unimpressive 33 percent. And start-up of the fuel processor at low temperature still needs improvement, although a battery can supply power temporarily.

What is more, the sulfur present in all gasoline (and in hydrogen made from it) will poison the catalyst in a proton-exchange membrane cell. In stationary phosphoric-acid fuel-cell systems, fuel is desulfurized before being transformed to hydrogen-rich gas. But gasoline cannot at present be cost-effectively desulfurized on board a vehicle.

Solutions might be developed. One possibility is to let hydrogen diffuse at high temperature and pressure through a membrane of palladium. Another idea is for manufacturers to produce a special sulfur-free synthetic fuel for use both in fuel-cell vehicles and in high-efficiency internal-combustion engines. But this proposal again raises questions about the needed infrastructure and its cost.

Not all major carmakers are committed to fuel cells. In June 1998 BMW announced that it preferred to move toward hydrogen-fueled internal-combustion engines, with liquid natural gas as an intermediate fuel. Yet a dedicated hydrogen-fueled internal-combustion engine would be less efficient than an optimized fuel cell and would produce some nitrogen oxides. Furthermore, until hydrogen produced from renewable energy sources such as solar power becomes widely available, it will be manufactured from natural gas and so cannot compete against the latter as a fuel.

In time, we are likely to see an infrastructure for delivering hydrogen for fuel-cell-powered vehicles. The result will be a more efficient, clean transportation sector, a reduction in imported oil and lower carbon dioxide emissions. A hydrogen delivery system will be built when it is technically feasible, affordable and necessary. But that point is still some years in the future. SA



MULTIFUEL PROCESSOR may be used in vehicles to convert gasoline or methanol to a hydrogen-rich gas mixture for fuel cells. Gas containing residual hydrogen, returned from fuel-cell anodes, is burned to heat fuel, water and air, which react on the high-temperature catalyst. Additional catalysts operating at successively lower temperatures reduce the amount of carbon monoxide and increase the hydrogen in the output stream.

GEORGE RETSECK

The Author

A. JOHN APPLEBY trained as a metallurgist and electrochemist at the University of Cambridge. He has studied electrochemical aspects of all the common types of fuel cells, including bioelectrochemical systems, for more than 30 years. Appleby worked on fuel cells and advanced batteries at the Marcoussis research center of the Compagnie Générale d'Électricité in France in the 1970s before joining the Electric Power Research Institute in Palo Alto, Calif., in 1978 to manage advanced fuel-cell technology. He was also consulting professor of chemical engineering at Stanford University. Since 1987 he has been professor of applied electrochemistry and director of the Center for Electrochemical Systems and Hydrogen Research at Texas A&M University.

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The Power Plant in Your Basement

In the past, stationary fuel cells were megawatt behemoths, designed for the electric utilities. Now they are being shrunk for homes and other modest applications

by Alan C. Lloyd

As deregulation of the electric utility industry dissolves the monopoly once held by most power generators, one repercussion has been increasingly long distances between some buyers and sellers of electricity. Nevertheless, within a decade or two, some customers may find themselves living in a home whose electricity comes not from a generating plant tens, hundreds or even thousands of kilometers away but rather from a refrigerator-size power station right in their own basements or backyards. Moreover, not just homes but shops, small businesses, hotels, apartment buildings and possibly factories may all be powered in the same way: by fuel cells in the range of five to 500 kilowatts.

Companies and industrial research laboratories in Belgium, Canada, Denmark, Germany, Italy, Japan, Korea and the U.S. have aggressive fuel-cell development efforts under way, and at least a few are already selling the units. In fact, a subsidiary of United Technologies has been offering fuel cells of up to 200 kilowatts for almost a decade. They have sold about 170 units, many of which are used for generation of both heat and power at industrial facilities or for backup power. They are also increasingly being used at wastewater treatment plants and in "green" facilities, which showcase environmentally sensitive technologies and design.

At present, the high cost of fuel cells has limited their use to these and very few other specialized applications, made feasible for the most part by generous government subsidies. Electricity from fuel cells now costs $3,000 to $4,000 per kilowatt, as opposed to $500 to $1,000 per kilowatt for the ordinary gas-fired combustion turbine commonly used by utilities. Another drawback is limited lifetimes; so far no commercial fuel cell has been in operation for more than 10 years, and utilities expect to get at least 20 years of useful service life from their generating equipment.

On the other hand, fuel cells have several very desirable features: they operate relatively cleanly and silently, can use a variety of fuels, and are generally unaffected by storms and other calamities. Because of these advantages, some observers believe fuel cells can become viable for a reasonably large group of applications when per-kilowatt prices reach about $1,500.

Developers will have to achieve a number of design and manufacturing improvements before fuel cells attain even that level of price and performance. The incentives for them to do so, however, are great. As concern mounts about the harmful environmental effects of greenhouse gases from conventional power plants, increasing use of fuel cells is expected to help move industrial societies toward a "hydrogen economy." Electricity will

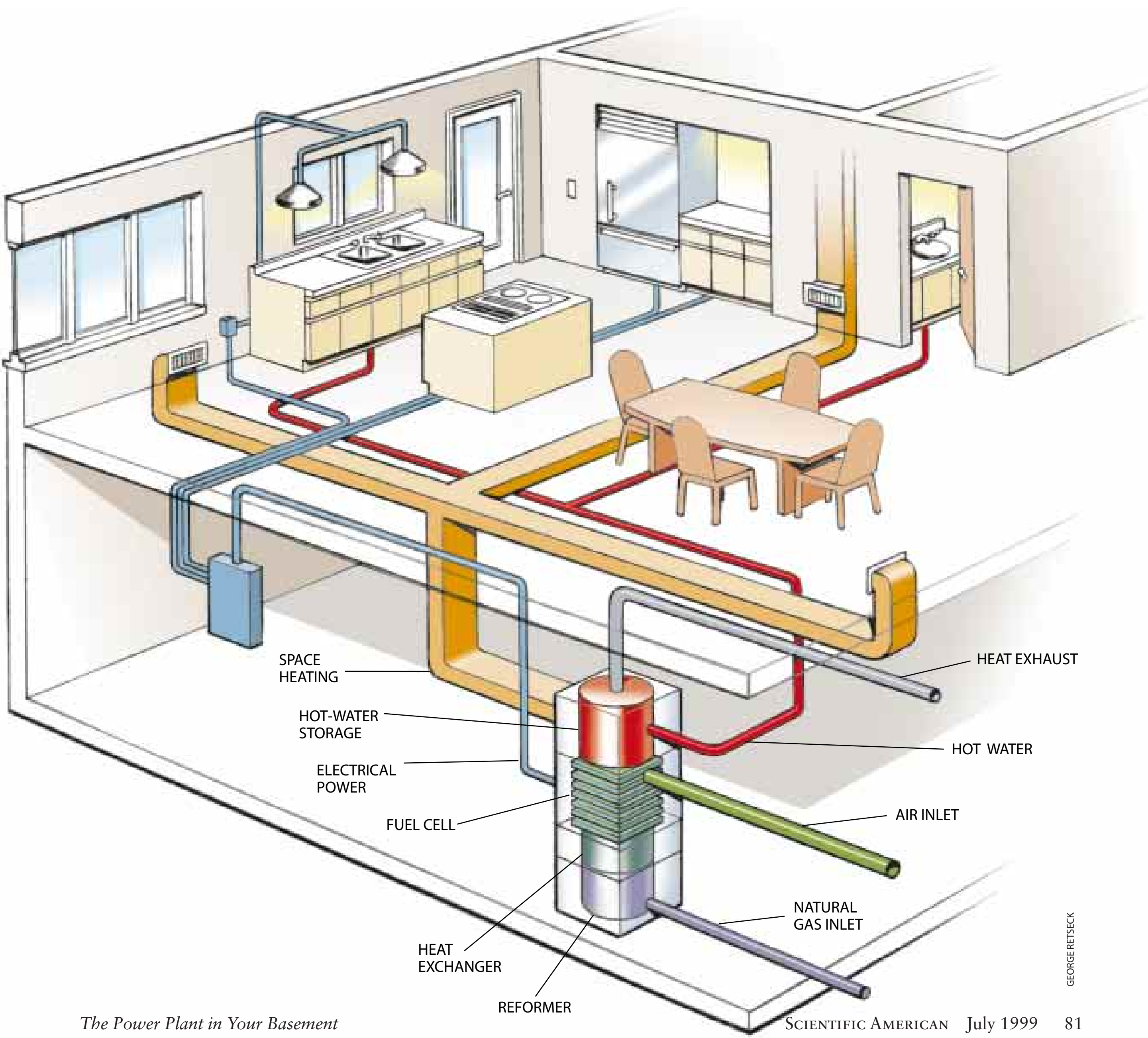
SOLID-OXIDE FUEL CELL could provide electricity, heat and hot water to a home. The device operates at 800 degrees Celsius (1,500 degrees Fahrenheit), and some of the heat necessary to sustain such a temperature could be captured and directed into the home's heating ducts (*orange*) and into the hot-water tank (*red*). This use of heat that would otherwise be wasted enables the system to put as much as 90 percent of the fuel's chemical energy to productive use. Such a unit, which would produce up to 10 kilowatts of electricity, is being designed by Hydrogen Burner Technology in Long Beach, Calif., which plans to begin selling it around 2003.

come mainly from fuel cells and other hydrogen-based devices and from solar cells, windmills and other renewable sources—which will also electrolyze water to contribute hydrogen for the fuel cells. The shift to this hydrogen-based energy infrastructure will accelerate in coming decades, particularly as oil supplies begin dwindling.

Have Fuel, Will Energize

Fuel cells are not new; in fact, the basic concept is well over a century old. Like batteries, fuel cells come in a variety of different types. Also like batteries, they produce an electric current by intercepting the electrons that flow from one reactant to the other in an electrochemical reaction. A fuel cell consists of a positive and a negative electrode separated by an electrolyte, a material that allows the passage of charged atoms, called ions.

In operation, hydrogen is passed over the negative electrode, while oxygen is passed over the positive electrode. At the negative electrode, a highly conductive catalyst, such as platinum, strips an electron from each hydrogen atom, ionizing it. The hydrogen ion and the electron then take separate paths to the positive electrode: the hydrogen ion migrates through the electrolyte, while the electron travels on an external circuit. Along the way, these electrons can be used to power an electrical device, such as a lighting fixture or a motor. At the positive electrode, the hydrogen ions and electrons combine with oxygen to form water. (Interestingly,



on the space shuttle, which gets its electricity from fuel cells, the by-product water is used for drinking.) To generate a useful amount of electric current, individual fuel cells are "stacked," like a club sandwich.

The device provides direct-current electricity as long as it is fed with hydrogen and oxygen. The oxygen typically comes from the ambient air, but the hydrogen usually comes from a system called a reformer, which produces the gas by breaking down a fossil fuel. One of the advantages of fuel cells is the great diversity of sources of suitable fuel: any hydrogen-rich material is a possible source of hydrogen. Candidates include ammonia, fossil fuels—natural gas, petroleum distillates, liquid propane and gasified coal—and renewable fuels, such as ethanol, methanol and biomass (essentially any kind of plant matter). Hydrogen can also be produced by solar, wind or geothermal plants. Even waste gases from landfills and water treatment plants will do. Reformers do release pollutants as they break down the fuel to make hydrogen. In comparison with a conventional gas-fired combustion turbine, however, the emissions are considerably less—typically a tenth to a thousandth, depending on the specific pollutant and how the emissions are controlled on the turbine.

Because a fuel cell's output is direct current, a device called an inverter is necessary to convert the DC into alternating current before the electricity can be of any practical residential or commercial use. In both the inverter and the reformer, power is lost, mostly as heat. Thus, although fuel cells themselves can have fuel-to-electricity efficiencies in excess of 45 percent, the energy losses in the reformer and inverter can bring the overall efficiency down to approximately 40 percent—about the same as a state-of-the-art gas-fired combustion turbine. As with the combustion turbine, however, recovering the waste heat—for example, to heat water or air—boosts the efficiency of the device significantly.

A popular misconception about fuel cells intended for stationary uses is that all of them are much more powerful than those being developed to propel automobiles. In fact, a fuel cell of just 40 to 50 kilowatts can easily meet the electrical needs of a large, four- or five-bedroom house or a small commercial establishment, such as a laundry. In comparison, because of the high level of power needed to accelerate a full-size car with four passengers, a fuel cell for a vehicle generally needs to put out at least 50 kilowatts [see "The Electrochemical Engine for Vehicles," on page 74]. The more demanding requirements for automotive cells have prompted some observers to speculate that in the future some rural dwellers may even get power by simply plugging their homes into their cars.

The misconception about stationary fuel cells being uniformly larger than ones for automobiles probably stems from some very large experimental units tested by electric utilities over the past 20 years. The most notable of these were a 4.5-megawatt fuel cell installed by Consolidated Edison in New York City in 1982, a 4.5-megawatt unit operated by Tokyo Electric Power in 1984, an 11-megawatt unit operated by the same company from 1991 to 1997 and a two-megawatt plant tested by Pacific Gas and Electric in Santa Clara, Calif., in 1995. The U.S. demonstrations were rather problematic; the northern California cell, for example, rarely generated more than one megawatt—only half the capacity it was designed for—and the New York City cell never operated at all. The Japanese experiences, however, were much more favorable; the 11-megawatt unit, for example, ran for approximately 23,000 hours.

JOCK POTTLE *Esto*; COURTESY OF FOX & FOWLE ARCHITECTS

4 TIMES SQUARE, under construction in New York City, will have two 200-kilowatt fuel cells on its fourth floor.

New Paradigm

Partly because of those difficulties, developers and proponents of stationary fuel cells have shifted to a paradigm based on a more decentralized approach. Smaller units, of less than 50 kilowatts, will supply power to individual homes, and larger systems of up to several hundred kilowatts will power commercial buildings and other enterprises. Industry sources estimate that sales of the smaller fuel cells for residences and small businesses could reach $50 billion a year in the U.S. by 2030.

Such a figure may represent a certain amount of wishful thinking. There are no single-family residences at present that receive their power from on-site fuel cells; however, three companies—Plug Power in Latham, N.Y., Avista Laboratories in Spokane, Wash., and Northwest Power Systems in Bend, Ore.—have units that provide electricity to demonstration homes. The first fuel cell installed permanently at a home in the U.S., a brick, ranch-style house near Albany, N.Y., went into operation a little over a year ago, in June 1998 [*see illustration on page 84*].

Larger systems aimed at industrial or commercial uses are also in the works. At least one company hopes to introduce a 500-kilowatt fuel cell in the next few years for stationary applications, and several others are developing or selling fuel cells rated at 200 to 250 kilowatts. A 250-kilowatt cell

FUEL CELLS COMPARED

ELECTROLYTE	Proton-exchange membrane	Phosphoric acid	Molten carbonate	Solid-oxide ceramic
OPERATING TEMPERATURE	80˚Celsius	Around 200˚ C	650˚ C	800–1,000˚ C
CHARGE CARRIER	Hydrogen ion	Hydrogen ion	Carbonate ion	Oxygen ion
REFORMER	External	External	Internal or external	Internal or external
PRIME CELL COMPONENTS	Carbon-based	Graphite-based	Stainless steel	Ceramic
CATALYST	Platinum	Platinum	Nickel	Perovskites (Titanate of calcium)
EFFICIENCY (percent)	40 to 50	40 to 50	Greater than 60	Greater than 60
STATUS OF DEVELOPMENT	Demonstration systems up to 50 kilowatts; 250-kilowatt units expected in next few years	Commercial systems operating, most of them 200-kilowatt; an 11-megawatt model has been tested	Demonstration systems up to 2 megawatts	Units up to 100 kilowatts have been demonstrated

RICHARD HUNT

could supply, for example, several stores in a strip mall or a small medical or corporate center.

Where larger loads are expected, multiple units can be linked. The developers of a building recently dedicated at 4 Times Square in New York City have installed two 200-kilowatt fuel cells to provide hot water for the building, light its facade and supply backup power [*see illustration on opposite page*]. The edifice is known as the Green Building because its developer, the Durst Organization, designed it partly to highlight technologies that are considered ecologically sound.

In a number of recent applications, fuel cells were chosen because their unusual features outweighed their high cost. For instance, a 200-kilowatt unit was installed at the police substation in New York City's Central Park. Use of a fuel cell obviated the expensive need to dig up the park to install underground power lines. In Nebraska the First National Bank of Omaha disclosed this past February that it would install four 200-kilowatt fuel cells at its Technology Center, where it processes credit-card transactions. The company chose fuel cells, backed up by auxiliary generators and by conventional electrical service from the local grid, because it needed extraordinarily high reliability for this application, in which even brief interruptions are quite costly.

Five Types of Cell

Of course, stationary fuel cells can be much larger and heavier than their mobile counterparts. So this market, though tiny today, has an unusual diversity of technologies being developed or sold. There are five main types of cell, each named after the electrolyte used in the system: phosphoric acid, molten carbonate, solid oxide, proton-exchange membrane and alkaline.

The phosphoric-acid fuel cell (PAFC) is the most mature technology of the five and the only one being offered commercially as of this writing in capacities above 100 kilowatts (all the fuel cells sold so far for commercial uses are PAFCs). Around the world, 12 organizations (seven in the U.S.) are marketing PAFCs or developing them. One of the largest is ONSI, a subsidiary of United Technologies, which has been deploying the units since the late 1980s. To date, the company has installed about 170 units, almost all of which are operating on natural gas. Some of these units have operated for tens of thousands of hours.

In the U.S., many of the purchases of ONSI fuel cells were subsidized under a program run by the Department of Defense and the Department of Energy since 1996. Buyers receive $1,000 per kilowatt or a third of the total project cost, whichever is lower. Already the program has distributed more than $18 million to the buyers and installers of more than 90 fuel-cell power plants.

A few large Japanese companies have sold approximately 120 PAFCs, with capacities ranging from 50 to 500 kilowatts. Several of these units have logged more than 40,000 hours of operational service.

In the U.S. and Japan, most PAFCs were purchased for power-generating installations that produce both heat and power. More recently, five other niche markets have sprung up, at landfills, wastewater treatment plants, food processors, power-generating facilities that cannot tolerate interruptions and green facilities (such as the aforementioned Green Building in New York City). In the first three applications, methane gas that would otherwise be an undesirable waste product is fed into the fuel cells; this free fuel helps to defray the cells' high purchase price.

The costs of PAFCs have been stalled for years now at about $4,000 per kilowatt—roughly three times what is believed to be necessary for the cells to

FUEL-CELL-POWERED HOME (*above*) in Latham, N.Y., gets its electricity from a refrigerator-size unit near the garage (*above right and at left*). The fuel cell, which is a variety known as proton-exchange membrane, supplies seven kilowatts—enough to meet much of the home's needs except during peak demand.

be competitive. This fact has prompted some observers to write off the technology as a dead end, and most fuel-cell companies established in the past three or four years are pursuing other technologies, such as molten carbonate, solid oxide and proton-exchange membrane.

Molten-carbonate fuel cells (MCFCs) and solid-oxide fuel cells (SOFCs) are similar in that they must be operated at high temperatures, in excess of 650 degrees Celsius (1,200 degrees Fahrenheit). As its name implies, the MCFC cannot operate until its electrolyte becomes molten, and the solid-oxide cells rely on the high temperatures to reform fuels internally and ionize hydrogen, without a need for expensive catalysts. On the other hand, this heat comes from the cells' output, reducing it marginally. Some engineers are envisioning residential applications in which waste heat from these cells would be captured and used to heat living spaces and water [*see illustration on page 81*].

The major U.S. players in MCFCs are the Energy Research Corporation (ERC) in Danbury, Conn., and M-C Power Corporation in Burr Ridge, Ill. ERC built the two-megawatt plant in Santa Clara, Calif., mentioned earlier. It operated for 3,000 hours; unfortunately, it rarely put out more than a megawatt. Recently ERC changed its focus to 250-kilowatt units. M-C Power demonstrated a 250-kilowatt unit in San Diego in 1997, although it managed to produce only a disappointing 160 megawatt-hours of electricity before requiring repairs. Approximately 10 Japanese companies are also pursuing MCFCs.

As for the SOFC, a total of 40 companies around the world are developing the technology. One of the largest was created in 1998 when Siemens acquired Westinghouse Power Generation; both companies had been working on versions of the SOFC. Other important U.S. developers of the SOFC include SOFCo, ZTek Corporation and McDermott.

Proton Exchange and the New Paradigm

If the phosphoric-acid, molten-carbonate and solid-oxide fuel cells are all in some ways vestiges of the centralized paradigm of deployment, the proton-exchange membrane technology represents the burgeoning decentralized approach. There is mounting enthusiasm for PEM cells in the wake of recent, significant reductions in the cost of producing their electrolytes and of the creation of catalysts that are more resistant to the degradation caused by carbon monoxide from the reformers.

The key component of a PEM is a thin, semipermeable membrane, which functions as an electrolyte. Positively charged particles—such as hydrogen ions—can pass through this membrane, whereas electrons and atoms cannot. A few years ago developers discovered that Gore-Tex, a material often used in outer garments, can be used to strengthen the membranes and significantly improve their operating characteristics.

That and other advances have prompted a flurry of activity in the devices. At present, some 85 organizations, including 48 in the U.S., are doing research on or developing PEMs. For example, Ballard Generation Systems in Burnaby, B.C., is working on a modular-design PEM that can be configured up to 250 kilowatts. The company hopes to begin selling the 250-kilowatt units in 2001.

General Electric's Power Systems division and the previously mentioned Plug Power have joined together to market, install and service PEMs worldwide with capacities up to 35 kilowatts. The joint venture expects to begin field-testing prototype units later this year and to install the first residential-size units early in 2001. Plug Power installed and operates a seven-kilowatt PEM fuel cell at a home in Latham, N.Y. (where two of the company's engineers live during the week).

Another company betting on PEMs is H Power Corporation in Belleville, N.J., which offers small units ranging from 35 to 500 watts. Besides promoting the cells for the usual residential uses, H Power has ventures targeting applications in backup power, telecommunications and transportation. In an unusual marketing strategy, it is even promoting fuel cells as security against the blackouts that some people fear will result from software glitches at the turn of the millennium. In another project, H Power is retrofitting 65 movable message road signs with fuel-cell power sources for the New Jersey Department of Transportation.

A few of the other PEM developers are Avista Laboratories in Spokane, Wash., which is working in conjunction with the engineering firm Black and Veatch; Matsushita Electric Industrial Company in Japan, which is focusing on a 1.5- to 3.0-kilowatt cell; and Sanyo, which has developed an appliance-like one-kilowatt PEM fuel-cell system that operates on compressed hydrogen. Sanyo also plans to develop a two-kilowatt unit using either a natural gas or methanol reformer.

Alkaline fuel cells, which have a relatively long history in exotic uses such as the space shuttle, are intriguing because they have efficiencies as high as 70 percent. So far their very high cost and other concerns have kept them out of mainstream applications. Nevertheless, a few organizations are attempting to produce alkaline units that are cost-competitive with other types of fuel cells, if not with other generation technologies.

Providing Premium Power

Other than continued subsidies, the best hope for fuel cells in the near future will be applications in which electricity is already expensive or in which waste gas can be used to fuel them. In fact, at current prices, it will probably take a combination of subsidies and unusually favorable circumstances. For instance, under an expanded federal government initiative in the U.S., purchasers of residential-size fuel-cell power plants may be eligible for federal help. In the past, federal agencies provided assistance only for the purchase of units of 100 kilowatts or more.

In the more distant future, concerns about global climate and related pressures to reduce emissions of carbon dioxide might even pave the way for large-scale use of fuel cells in the developing world. In a paper presented last year, Robert H. Williams of the Princeton University Center for Energy and Environmental Studies proposed that fuel cells might play a role in the electrification of China, whose 1.2 billion people have one of the world's lowest per capita rates of electricity usage. China has vast reserves of coal, which, Williams noted, could be turned into a supply of hydrogen-rich gas well suited to fuel cells. The challenge would be to "decarbonize" the coal during gasification. This decarbonization would produce waste carbon dioxide—a key greenhouse gas. So engineers and geologists would have to sequester it somehow, separating it permanently from the environment.

Because of such issues, any large-scale deployment of fuel cells in a developing country could be a decade off. But in the developed world over the next several years, improvements in the proton-exchange, molten-carbonate and solid-oxide technologies will enable fuel cells to carve out new niches and expand the small ones they already occupy. As they do so, they will begin ushering in a cleaner, more environmentally benign hydrogen economy—and perhaps not a moment too soon.

The Author

ALAN C. LLOYD is chairman of California's Air Resources Board, part of the state's Environmental Protection Agency. When this article was commissioned, he was executive director of the Energy and Environmental Engineering Center at the Desert Research Institute in Nevada. Before that, he was chief scientist at the South Coast Air Quality Management District in California. He wishes to thank the U.S. Fuel Cell Council and Fuel Cells 2000 for their help in the preparation of this article.

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Replacing the Battery in Portable Electronics

Batteries are cumbersome and expensive. Miniature fuel cells could supplant them in cellular phones, laptop computers, camcorders and other consumer products

by Christopher K. Dyer

Despite major advances in portable electronics, the battery has changed little. Even so, small batteries remain the only choice for consumer products that need up to about 20 watts of power, for everything from toys to laptop computers. But batteries can be heavy and expensive, and they can expire without warning, requiring either replacement (presenting a disposal problem) or recharging (taking hours of precious time). Is there no better alternative?

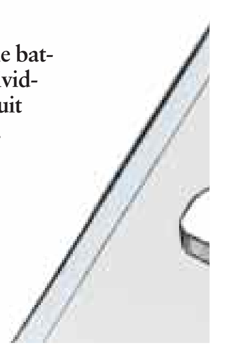
Ironically, the answer may lie with another invention from the past century: fuel cells. Theoretically, the technology has the same consumer-friendliness as batteries: quiet and clean conversion of a material's chemical energy into electricity. But the real advantage of fuel cells lies in their amazing ability to liberate electrical energy from the hydrogen atom. A fuel cell running on methanol could provide power for up to 20 times longer than traditional nickel-cadmium batteries in a comparably sized package but at a lower price and for a small fraction of the weight. Another benefit is that fuel cells do not require lengthy recharging; they can instead be replenished quickly, simply by adding more fuel.

In the past, much research interest has focused on automotive fuel cells [see "The Electrochemical Engine for Vehicles," on page 74]. But the internal-combustion engine, a technology that has been honed continually over decades, has proved difficult to beat. A greater area of opportunity might be with smaller applications, where the main competition is batteries. In fact, recent attempts to miniaturize fuel cells could lead to substantial improvements, possibly cellular phones that can run continuously for months on standby power and laptop computers that allow more than 100 hours of operation from a single, compact device. But as fuel cells shrink, various engineering problems become increasingly acute. Indeed, miniaturization requires a tricky balance of several factors, including power, size, convenience and cost.

Feats of Electrochemistry

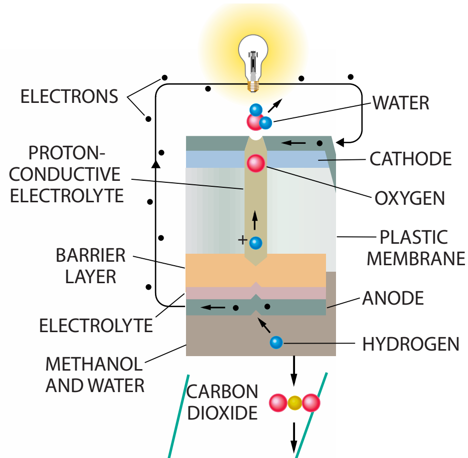
Actually, fuel cells and batteries are more alike than different. They both rely on electrochemistry to extract electricity from the stored chemical energy of a material. In a typical fuel cell, the process begins with the aid of a catalyst that helps to liberate electrons from fuel molecules, leaving behind positively charged ions. The electrons travel from one electrode to another through an external circuit while the newly formed ions flow through a material called an electrolyte that is sandwiched between the two electrodes. The two parallel currents of electrons (negative) and ions (positive) offset each other, balancing the separated

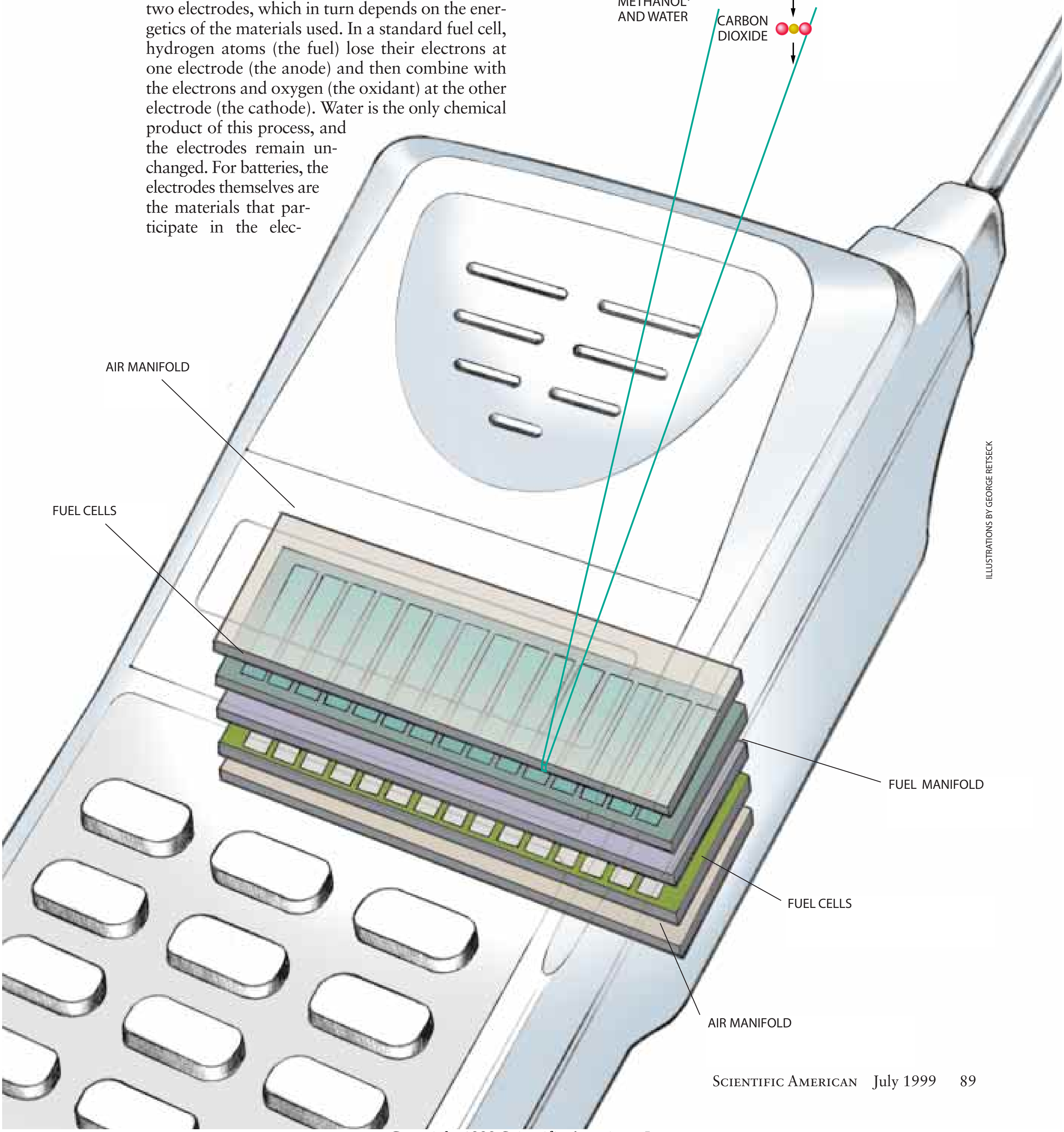
MICRO FUEL CELL for a cellular phone fits within the same space currently occupied by a rechargeable battery (*right*). The compact power source contains a row of cells fabricated on two thin plates. The individual cells consist of several layers (*top right*) that are manufactured in a similar fashion to electronic circuit boards and chips. Manhattan Scientifics plans to build a prototype of the device by the end of the year.



charges. This direct extraction of electrons to generate electrical power from chemicals is a quiet, simple, and relatively cool and clean process; its efficiency can be up to three times higher than that of a system powered by a small internal-combustion engine.

The power that a fuel cell or battery can generate is directly related to the voltage between the two electrodes, which in turn depends on the energetics of the materials used. In a standard fuel cell, hydrogen atoms (the fuel) lose their electrons at one electrode (the anode) and then combine with the electrons and oxygen (the oxidant) at the other electrode (the cathode). Water is the only chemical product of this process, and the electrodes remain unchanged. For batteries, the electrodes themselves are the materials that participate in the elec-





ILLUSTRATIONS BY GEORGE RETSECK

trochemical reaction (for example, the nickel oxyhydroxide and cadmium in a NiCd unit).

With compact lithium batteries designed for portable electronics, practical voltages do not currently exceed three to four volts. Hydrogen-based fuels do not develop much more than one volt, but because of their lower weight and volume they can nonetheless contain substantially more electrical energy in a similar package.

A Battery of Comparisons

Indeed, when comparing fuel cells with batteries, the primary factor is not basic efficiency, because both are excellent at extracting electricity from chemicals. Fuel cells, though, have a natural advantage in that they can use energy-rich fuels containing hydrogen. For a given weight, the pure liquid form of hydrogen contains about 800 times the electrochemical energy of nickel-cadmium [*see table on page 92*]. The problem, though, is that liquid hydrogen must be kept at cryogenic temperatures, below about –250 degrees Celsius (–420 degrees Fahrenheit), making the substance clearly unsuitable for consumer products.

But compounds containing hydrogen are also impressive. Theoretically, just one liter of methanol could supply about 5,000 watt-hours, enough to run a laptop computer continuously for more than a week. A comparable volume of lithium-ion, the most energy-dense rechargeable battery, has less than a tenth of that energy.

Furthermore, a fuel cell generally needs to stow just fuel (such as methanol) because the oxygen required for the electrochemical reaction can usually be taken from the surrounding air. Batteries, on the other hand, must typically store both reactants as two bulky solid materials at the cathode and anode, adding to the cost, size and weight of the units.

Convenience is yet another consideration. Fuel cells can be replenished quickly by simply adding more fuel, perhaps by inserting a new ampoule of methanol or by replacing a cartridge of solid hydride. Batteries must be recharged slowly, or they must be discarded altogether. In this sense, fuel cells offer the convenience of an automobile's internal-combustion engine—rapid refuelability for essentially continuous use.

And then there are financial factors. Fuel cells were once prohibitively expensive, which limited their use to must-have niches, such as for lightweight, water-producing power supplies in manned spacecraft, such as the space shuttles. But sophisticated engineering has recently driven costs down considerably. For one thing, scientists have dramatically reduced the amount of expensive platinum required for the catalysts. With energy-dense batteries, meanwhile, the cost per energy unit has actually gone up because of the higher prices of the advanced materials used. For these reasons, fuel cells may one day replace batteries for many consumer applications.

The following numbers help to reveal why. In electronic products requiring less than 100 watts, the cost of providing that power by battery is relatively expensive, not to say impractical, for any length of time. A 20-watt nickel-cadmium battery with a mass of half a kilogram (about one pound) will last about one hour and cost roughly $20. For longer usage, a comparable lithium-ion battery can provide the same amount of power for about three hours but costs at least four times more. In contrast, a similarly capable fuel cell using methanol could run for around 30 hours, and the basic materials for the device and fuel might cost as little as $2 to $5.

Of course, the price tag of any fuel cell must also include its manufacturing cost, and therein lies the difficulty. Indeed, designing a miniature fuel cell that can be mass-produced cheaply has been a formidable task. The engineering challenges are enormous, requiring no small amount of innovation.

The Creep of Complexity

Basically, a fuel cell is a very simple device—all that is needed is hydrogen fuel, a supply of oxygen, two catalytic electrodes and an electrolyte. From here, though, complexity creeps in.

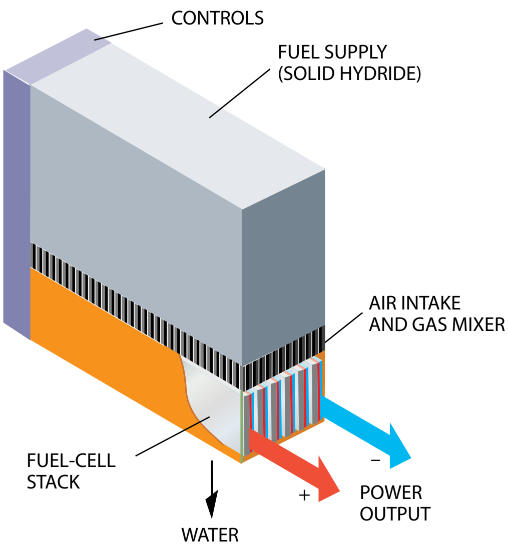
Because an individual fuel cell typically cannot generate sufficient power by itself, multiple cells are usually stacked or strung together. But the arrangement complicates the internal plumbing of the device, particularly with respect to the subassemblies needed to store and control the fuel and oxygen supplies. Also, a series of cells can run hot, requiring a cooling system—an additional complication.

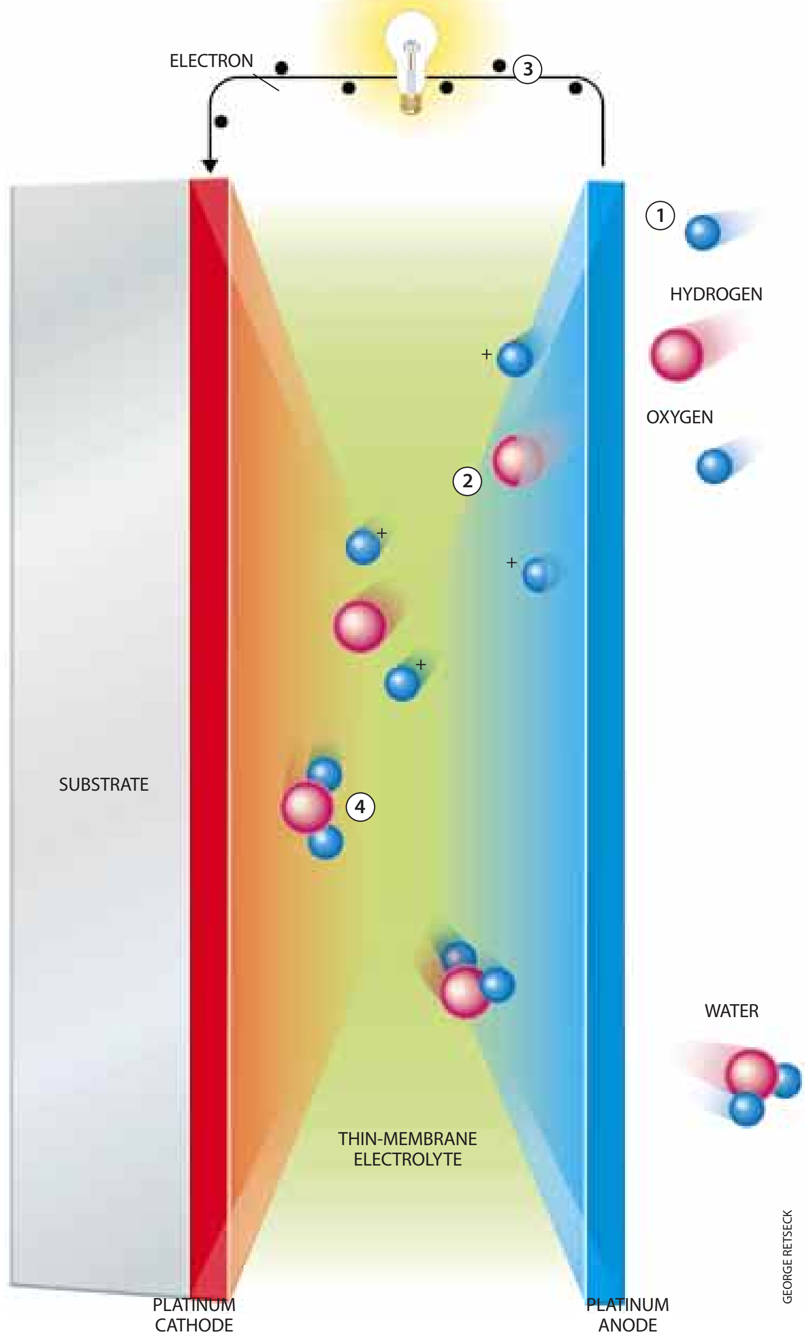
These issues become increasingly severe as the fuel-cell stack is shrunk to fit into camcorders and handheld cell phones. In fact, for current designs, the subsystems add more weight and volume than the stack itself. Thus, the challenge of miniaturization is one of engineering.

A crucial step in building any fuel cell is the choice of fuel, because that decision will have important implications for the overall system. Hydrogen is the easiest substance for a fuel cell to oxidize, but in its pure form (either as a gas or a cryogenic liquid) it is impractical and even dangerous for portable consumer applications.

As an alternative, hydrogen can be stored in a range of metals. The best known of these is palladium, but many cheap alloys, such as those that contain lanthanum and nickel or iron and titanium, are also available. One requirement is that the hydrogen be extractable quickly and at ambient temperatures and pressures, thus obviating any additional subsystems. An advantage of using a metal hydride is that the material can be replenished. At 0 degrees C, metal hydrides can absorb gaseous hydrogen within about 30 minutes. In the future, home electrolyzers of water could play a role in supplying the necessary hydrogen.

Chemical hydrides, such as those containing lithium, aluminum, sodium or boron, also provide a very convenient source of hydrogen, and they are





THIN-FILM DESIGN enables this miniature fuel cell to generate power by drawing both hydrogen and oxygen from the same gas mixture, as opposed to traditional designs, which require separate supplies. The device consists of a stack of six cells (*above*), each containing an extremely thin (less than one micron) membrane. This porous layer is the electrolyte that separates the cathode and anode (*right*). At the anode, hydrogen loses its electrons (*1*) and travels through the membrane toward the cathode. Oxygen also diffuses through the thin electrolyte (*2*) while the freed electrons pass through an external circuit (*3*). At the cathode, the hydrogen ions, electrons and oxygen combine (*4*), forming water.

lighter than their metallic counterparts. But they are expensive and not reusable, and they leave a caustic residue.

Much cheaper are liquid organic hydrides, such as decalin and methylcyclohexane. Extracting hydrogen from them, however, requires a catalyst and temperatures greater than 200 degrees C.

A hydrocarbon of greater promise is methanol. In fact, after many years of investigation, researchers have concluded that methanol would be the best choice for small fuel cells. The energy-rich alcohol is relatively cheap (it can be obtained from natural gas or biomass for about the same price as gasoline) and convenient. A cell phone might, for example, run on inexpensive ampoules of methanol that could be purchased from a drugstore or supermarket.

There is, however, one obstacle. For extraction of its hydrogen, methanol typically requires reformation, a sophisticated chemical conversion. The process results in two by-products: carbon dioxide and a small amount of carbon monoxide. Fortunately, no nitrogen oxides are produced.

But even a small amount of carbon monoxide is problematic because it binds with platinum, poisoning the metal's catalytic action. Consequently, another step for removing the deleterious gas is required. Although small reformers with primary (for the hydrogen extraction) and secondary (for the carbon monoxide cleanup) stages have recently been developed, such devices obviously burden a fuel-cell system with additional complexity and cost.

Special catalysts can enable a fuel cell to consume methanol directly, without a reformer, at temperatures below 100 degrees C. But the process limits the device's power. Also, leakage of methanol to the cathode will further decrease power and efficiency. To combat this degradation, one strategy calls for diluted methanol in the fuel supply. But this approach would negate the advantage of using the energy-rich alcohol in the first place. Thus, some experts believe the ultimate commercial acceptance of methanol will depend on the development of a membrane that is impermeable to the substance.

Never Too Thin

Several companies, including Ballard Power Systems in Burnaby, B.C., and H Power in Belleville, N.J., have extended conventional fuel-cell technology to small systems (20 to 100 watts). Even though the prototypes are but early, tentative steps into portable devices, they are already comparable with lithium-ion batteries.

Use of thinner fuel-cell components and smaller, lightweight subsystems should result in miniature fuel cells that supersede batteries. Indeed, a number of research groups around the world have been building such promising systems. Much of this work is being kept under wraps, but some preliminary information reveals strikingly different approaches.

The Fraunhofer Institute for Solar Energy Systems in Freiburg, Germany, in conjunction with Siemens PC Systeme, has built a prototype fuel cell for laptop computers. The device consists of five fairly thin plates, each containing five fuel cells in series. Using a solid metal-hydride fuel source, this array of 25 cells is able to generate 20 watts. The device, which already performs slightly better than lithium-ion batteries do, is currently being refined.

In a radically different approach, Robert Hockaday of Manhattan Scientifics in New York City is developing a micro fuel cell [*see illustration on page 89*] that could be mass-produced using manufacturing techniques from the electronics industry. In his design, a thin film of plastic (only 25 microns thick) is bombarded with nuclear particles and then chemically etched to form fine pores (the cells), into which a polymeric electrolyte is added. Next, chipmaking techniques, including vacuum deposition, help to layer and etch onto the plastic structure a preferentially permeable barrier (to thwart methanol leakage), the two electrode plates, a catalyst material and a conductive grid to connect the individual cells.

The fuel cells are able to ingest diluted methanol directly. At present, they are delivering just a meager amount of power, but they could be packaged together into small volumes to better the performance of lithium-ion batteries. Start-up is a tad sluggish, however, requiring the assistance of a battery that would also help accommodate any subse-

THE ENERGETIC POTENTIAL OF FUEL CELLS

	STORED ELECTROCHEMICAL ENERGY (in watt-hours)	
	By mass (per kilogram)	By volume (per liter)
FUEL CELLS		
Decalin ($C_{10}H_{18}$)	2,400	2,100
Liquid hydrogen	33,000	2,500
Lithium borohydride ($LiBH_4$ and $4H_2O$)	2,800	2,500
Solid metal hydride ($LaNi_5H_6$)	370	3,300
Methanol	6,200	4,900
Hydrogen in graphite nanofibers	~16,000	~32,000
RECHARGEABLE BATTERIES		
Lead acid	30	80
Nickel-cadmium	40	130
Nickel-metal hydride	60	200
Lithium-ion	130	300

Notes: For hydrogen and hydrocarbon fuels, complete oxidation is assumed. Values are theoretical (thermodynamic maximum), except for metal hydride and graphite nanofibers. The figures given for those two materials are for the extractable hydrogen. Graphite nanofibers are a new development that is currently being investigated; a density of two grams per cubic centimeter is assumed. For batteries, the values are the actual electrochemical energies available.

quent surge in the demand for power. If the cost of the multistep manufacturing process can be kept low, this novel approach could eventually result in inexpensive devices.

The U.S. government has also been keen on the direct-methanol approach, with several programs under way at universities and government laboratories. In particular, a joint effort between the Jet Propulsion Laboratory in Pasadena, Calif., and the University of Southern California has developed a fuel cell that has a polymer electrolyte and a special anode catalyst: an alloy of platinum and ruthenium, which is cheaper than pure platinum. Prototypes with a power output of 10, 40 and 150 watts and higher have operated for more than eight days continuously at 90 degrees C.

Unfortunately, the fuel cells can tolerate a maximum of only about 2 percent methanol in water. But the devices cleverly return by-product water from the cathode side to a very small chamber near the anode, where it is used to dilute pure methanol, thus increasing the efficiency of the device while minimizing its size. The present power-density level for the overall system is a respectable 30 watts per liter, and the goal is to increase that figure by more than threefold by the end of the year.

My own interest has been in a thin-film fuel cell [*see illustration on page 91*] that generates power from a gas mixture that contains both hydrogen and oxygen, as opposed to conventional designs, which require separate gas supplies. The simpler operation should enable a cheaper and more compact system.

Originally announced in 1990, the approach relies on a gas-permeable electrolyte that is extremely thin (less than one micron). This membrane is sandwiched between two thin layers of platinum (the two electrodes), one that is exposed to the gas mixture and one that sits on a substrate. This fuel cell is probably the thinnest and lightest built thus far.

In the device, hydrogen oxidizes (or loses electrons) much faster at the exposed platinum electrode than at the other platinum electrode, because the former is in direct contact with the gas mixture. Thus, at the exposed electrode (the anode), there is an overwhelming supply of hydrogen ions that then rapidly diffuse through the membrane to the "slower" electrode (the cathode) on the substrate immediately below. There, in concert with the externally transferred electrons, the hydrogen ions combine with oxygen that has diffused through the porous membrane. This electrochemical reaction, called reduction, produces water and results in a positive potential of about one volt. The mechanism relies on the closeness of the two electrodes; otherwise the hydrogen ions are unable to reach the cathode from the anode.

Hypothetically, with this thin-film design, a single cell (essentially the three-layer sandwich of platinum, electrolyte and platinum) with a surface area of 16 square centimeters could generate up to 0.85 watt of power. Thus, a stack of six cells with a total depth of just one centimeter could deliver up to five watts (three volts with a current of 1.7 amperes). This design could enable extremely compact fuel cells to deliver up to 1,000 watt-hours per liter from a solid hydride and up to 1,400 watt-hours per kilogram from methanol—substantially superior performance to that of lithium-ion batteries.

These various miniature fuel cells are still in the very earliest stages of development. An important point worth noting is that although initial prototypes have been built, no one has yet definitively demonstrated a compact device that could be mass-produced at a cost significantly lower than that of comparable rechargeable batteries.

A New Fuel Source?

The commercialization of small fuel cells would accelerate tremendously if scientists could find a better source of hydrogen. Methanol is rich in energy, but its use is complicated by several engineering problems, and metal hydrides provide merely an adequate, if unspectacular, storage medium.

Recently Terry Baker of Northeastern University announced a form of carbon called graphite nanofibers that boasts almost unbelievable capacity: one gram of the material is reportedly able to deliver 10 liters of hydrogen. Such incredible energy density (equivalent to about 16,000 watt-hours per kilogram) would make other materials pale in comparison. In theory, just half a liter of this incredible substance could power a 20-watt laptop computer continuously for more than a month!

Although this work needs to be more widely reproduced, the use of a new material such as graphite nanofibers illustrates the enormous potential of fuel cells as a portable power source. Ironically, the discovery that certain carbon materials could accommodate significant amounts of lithium was a major finding that greatly advanced battery technology.

The Author

CHRISTOPHER K. DYER, formerly with AT&T Bell Laboratories and then Bell Communications Research, now works for Motorola. Until 1998, he was president of Red Bank Research Company, a joint venture of Bellcore and Motorola that developed his thin-film fuel-cell invention for application in portable electronic devices. He is a graduate of the University of Cambridge and is the U.S. editor of the international *Journal of Power Sources*.

Further Reading

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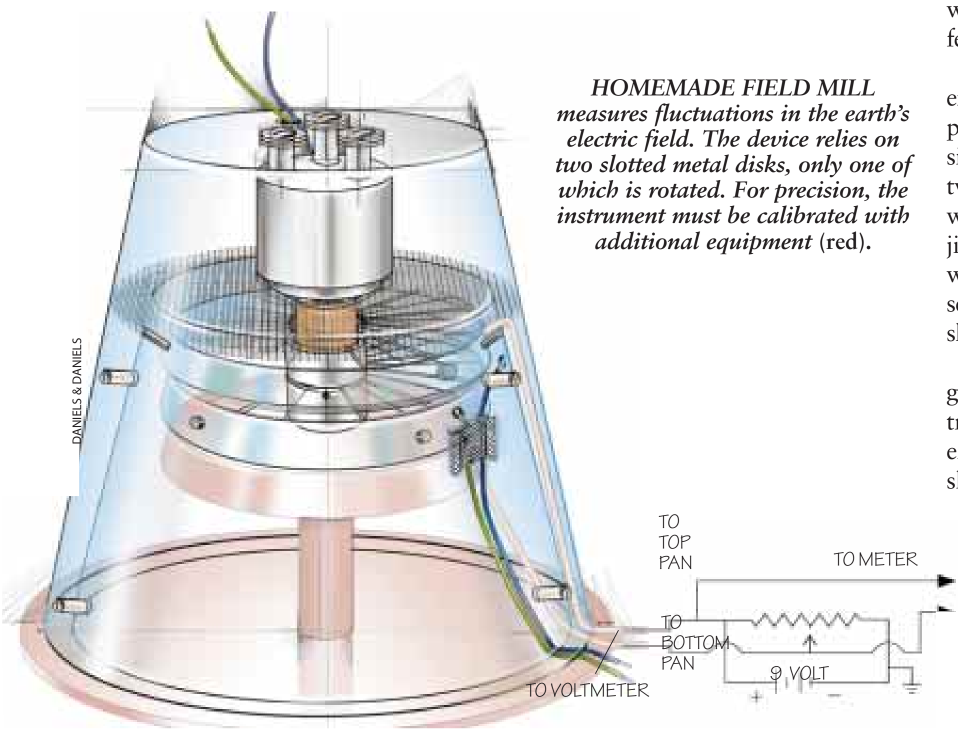
by Shawn Carlson

Detecting the Earth's Electricity

If electric fields were visible, then even the most barren spot on the earth would provide an awesome sight. Standing on a hilltop, you would see a forest of electric-field lines shooting out of the ground everywhere, stretching up to the ionosphere. You could watch them sweep across the horizon to gather under storms. In fact, the earth's electric field is far more dynamic—and, for me, more interesting—than its magnetic counterpart.

This electrical phenomenon is generated by the thousands of thunderstorms that pummel our planet continuously with 100 lightning bolts a second and that also deliver to the ground a tremendous amount of charge on raindrops [see The Amateur Scientist, August 1997]. As a result, we live atop an ocean of negative charge that generates an electric field of approximately 100 volts per meter elevation. In other words, when you are standing, your head is about 200 volts greater than your feet. And when a thunderstorm passes overhead, the electric fields can increase to thousands of volts per meter. Fortunately, there is very little free charge (unattached electrons and positive ions) in the air around us, and so these high voltages cannot create any large currents, which would otherwise surely electrocute us.

To monitor the earth's electric field, I have developed an accurate home-built instrument that can be constructed for under $50. The device is basically an inexpensive incarnation of a field mill, which measures electric fields by using two slotted metal disks mounted coaxially and vertically with their surfaces almost touching. One disk is fixed and grounded to the instrument's case, and the other is rotated at high speed. (Grounding the instrument to the case, and not to the earth's surface, lets the experimenter take measurements anywhere, even from an airplane high in the atmosphere.) When the slots are not aligned, the local electric field reaches the upper plate and drives some of its free charge into ground. But because conductors block electric fields, the lower plate shields the upper plate when the metal sections line up, thereby allowing the banished charges to return. Rotating the lower plate thus causes a current that surges back and forth in the ground wire, and these electrical pulses can be detected with an inexpensive circuit.

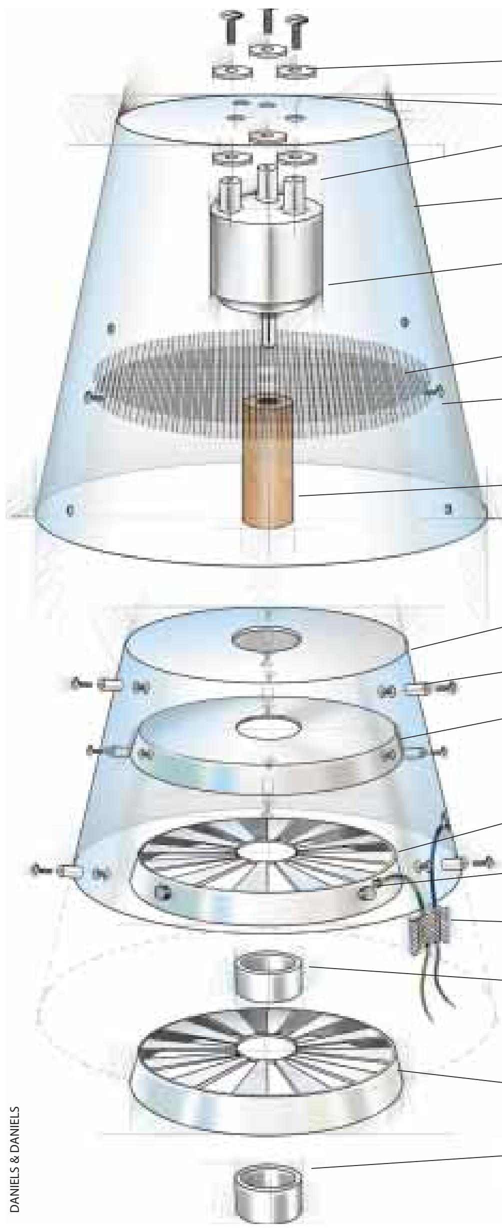


***HOMEMADE FIELD MILL** measures fluctuations in the earth's electric field. The device relies on two slotted metal disks, only one of which is rotated. For precision, the instrument must be calibrated with additional equipment* (red).

I improvised a field mill by taking two steel cake pans and cutting out a dozen equally spaced 15-degree wedges (the slots) from their circular bases. To rotate one of the pans, I used a surplus high-speed electric motor. These motors typically deliver between 1,000 and 7,000 revolutions per minute. At those rates and with the cake pans cut with 15-degree wedges, the earth's field generates nanoampere-size current surges in the ground wire at frequencies between 200 hertz (for 1,000 rpm) and 1,400 hertz (for 7,000 rpm). Such a signal can be observed easily with a circuit containing a transconductance amplifier and a peak detector. (Details of the circuit can be found at www.sciam.com on the World Wide Web, or send a self-addressed, stamped envelope to The Amateur Scientist, "July 1999," Scientific American, 415 Madison Avenue, New York, NY 10017.) In fact, my homemade instrument can readily detect shifts a mere thousandth of the ambient field. Furthermore, a computer analyzing the data will be able to follow the fluctuations with a performance rivaling that of professional instruments.

You can build the device over a weekend. First, use a protractor to lay out the pattern of 15-degree wedges on the inside of one cake pan. Then clamp the two pans firmly against a circle of plywood (to facilitate the cutting) and use a jigsaw to obtain two identical sets of wedges. Select one pan as the stationary sensor disk and the other as the rotating shield.

Because an electric motor invariably generates intolerable amounts of electromagnetic clutter, you must take several countermeasures. Even the metal shaft gives off such deleterious energy, and if the rotating shield pan were connected directly to the shaft, this radiation would spew out between the two pans, where the instrument is most vulnerable to noise. To avoid such degradation, add to the shaft a nonconducting extension, *VERTICAL MOUNTING of various parts, including two cake pans with wedges cut from their bases, is required to construct a homemade field mill.*



DANIELS & DANIELS

such as a wooden dowel 2.5 centimeters (one inch) in diameter. Use a drill press to bore a precision hole along the exact centerline of the dowel and then epoxy the shaft inside it. Next, electrically isolate the motor by mounting it coaxially, with Teflon screws and washers, to the inside of an upside-down metal trash can like the ones found in offices and schools. You can capture most of the radiated gunk with two layers of aluminum window screen.

Next, cut off part of a second metal trash can so that it will fit within the first can with the motor attached. Then drill a hole through the centers of the sensor pan and a third cake pan (for calibrating the instrument) that can amply accommodate the dowel. During the calibration process, you will need to charge the third pan, so affix a wire to its outside surface by using a conducting metallized epoxy. Three small rubber gasket spacers wedged between the sides of the sensor and calibration pans will hold them close together without their touching. Bolt them as a unit to the inner trash can by using insulating standoffs and drill a hole in the can to take the wire out.

The circuit must be attached to the inner trash can at a location directly below the sensor pan. To reduce electrical interference, shorten as much as possible the wires that connect the sensor pan to the circuit and the circuit to the inner trash can. Also, completely enclose the circuit with a patch of aluminum screen. Remember that you need to force all the signal current to pass through the amplifier, so make sure that the ground wires are the only electrical link between the sensor pan and the trash can.

Install the entire assembly inside the outer trash can by again using insulating standoffs. Then, from the end of a PVC pipe of 2.5-centimeter inner diameter, cut a spacer that is precisely one centimeter long. Thread the spacer over the wooden dowel and rest it against the sensor pan; epoxy the spacer to only the dowel. (If you bond it to the sensor pan, the shaft will not rotate.) Finally, cut a hole in the center of the shield pan so that you can secure it onto the dowel between the spacer and a second piece of PVC pipe.

To calibrate the instrument, you first need to glue a fourth cake pan coaxially to one end of a dowel and a large pizza pan (for screening out the earth's electric field) to the other end. Insert this implement within the trash-can assembly. A voltage placed between the top and bottom cake pans creates a field that approximates the earth's. With a two-centimeter spacing between those pans, a two-volt difference creates a 100-volts-per-meter field inside the instrument. You can calibrate the device at the low end of its scale with nine-volt batteries and a rheostat. Simulating the field generated by a powerful thunderstorm requires a 200-volt power supply, which you can find at most electronics surplus shops for less than $100. But keep in mind that these devices can deliver enough current to kill, so use extreme care.

Use your homemade field mill outdoors, far away from buildings, either rigidly suspended from a pole or resting level on an insulated ring. Either way, make sure its opening has an unobstructed view of the ground. If you run the signal into your home through a coaxial cable, you will be able to monitor the field comfortably in all kinds of weather.

For more information about this and other projects, check out the Society for Amateur Scientists's Web page at www.thesphere.com/SAS/WebX.cgi. You may also write the society at 4735 Clairemont Square, Suite 179, San Diego, CA 92117, or call 619-239-8807.

by Ian Stewart

The Art of Elegant Tiling

Mathematics and art have many points of contact, but none is more beautiful than the concept of symmetry. The mathematician's approach to symmetry is a little too rigid for most forms of visual art, but it can be readily applied to any art form that features repetitive patterns. Wallpaper, fabrics and tiles are familiar examples, and all of them can rise to great artistic heights. Tiles and wallpaper designed by 19th-century British artist William Morris are displayed in London's Victoria and Albert Museum. The Edo-Tokyo Museum possesses some absolutely outstanding examples of patterned kimonos, and the Alhambra palace in Granada, Spain, is renowned worldwide for its intricate tiled patterns.

Although the basic mathematics of symmetry and tilings was worked out long ago, new discoveries continue to be made, often by artists. Rosemary Grazebrook, a contemporary British artist, has invented a remarkably simple tiling system that is eminently practical and different enough from the usual rectangular tiles to be interesting. It is also ingenious and, in the right hands, beautiful.

The mathematical definition of symmetry is simple but subtle. A symmetry of a design is a transformation that leaves the design unchanged. For example, the transformation "rotate by 90 degrees" leaves a square unchanged; the transformation "reflect from left to right" leaves the human form (superficially) unchanged. A design may have many different symmetries: together they constitute its symmetry group.

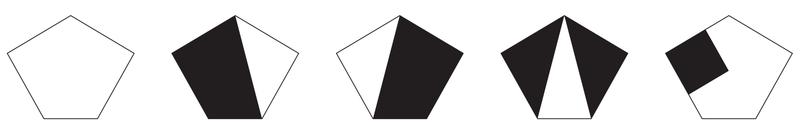
There are also many kinds of tilings. The type that has traditionally attracted the most interest from mathematicians is based on a two-dimensional lattice—in effect, a planar crystal. Ironically, the math here was first worked out in the hugely difficult case of three dimensions and only much later carried through in two dimensions. In 1891 Russian crystallographer E. S. Fedorov proved that lattices in the plane fall into 17 distinct symmetry types [*see illustration on page 98*]. The same goes for wallpaper designs and textile patterns. It may seem strange to say this when any home improvement store can show you dozens of thick books of wallpaper samples and rack after rack of tiles. In most cases, however, the differences lie in such features as color, texture and the nature of the underlying design elements. Important as these are to the customer, they do not affect the symmetry of the pattern, except that they may be constrained by it. For instance, square bathroom tiles bearing an image of a duck will have the same symmetry as similar tiles with the image of a length of seaweed—unless extra symmetry occurs in the images themselves.

Some patterns do not possess any great degree of symmetry, and these I shall ignore here. Among them are important modern discoveries such as the famous Penrose tiles, which completely cover the plane but never repeat exactly the same arrangement. The patterns of concern here are based around one "fundamental region"—a design that is repeated indefinitely in two independent directions. For example, imagine an array of standard square tiles, as seen in so many bathrooms. Our imaginary bathroom, however, has infinitely large walls, so the pattern never stops. Pick some tile. The pattern of that tile repeats in both the horizontal and vertical directions and in combinations of those. In fact, if you displace the tile by any whole number of tile widths horizontally, to the left or the right, and then by any whole number of tile widths vertically, up or down, you'll find an identical tile. So the pattern repeats in two distinct directions. Here those directions happen to be at right angles to each other, but this is not a general requirement.

The existence of two such directions is what we mean by a lattice. Lattice symmetry is natural for wallpaper and textiles because they are usually made by forming a long roll of material along which the same pattern repeats over and over again—perhaps printed by a revolving drum or woven by a machine that repeats a fixed loop. When the paper is stuck to a wall or if the material is sewn together to cover a wider region, it is usual to match the pattern along the join. But this matching may involve what interior decorators call a "drop": you slide the paper sideways and then up or down by some amount. If there is a drop, then the lattice repeats along two directions that are not at right angles.

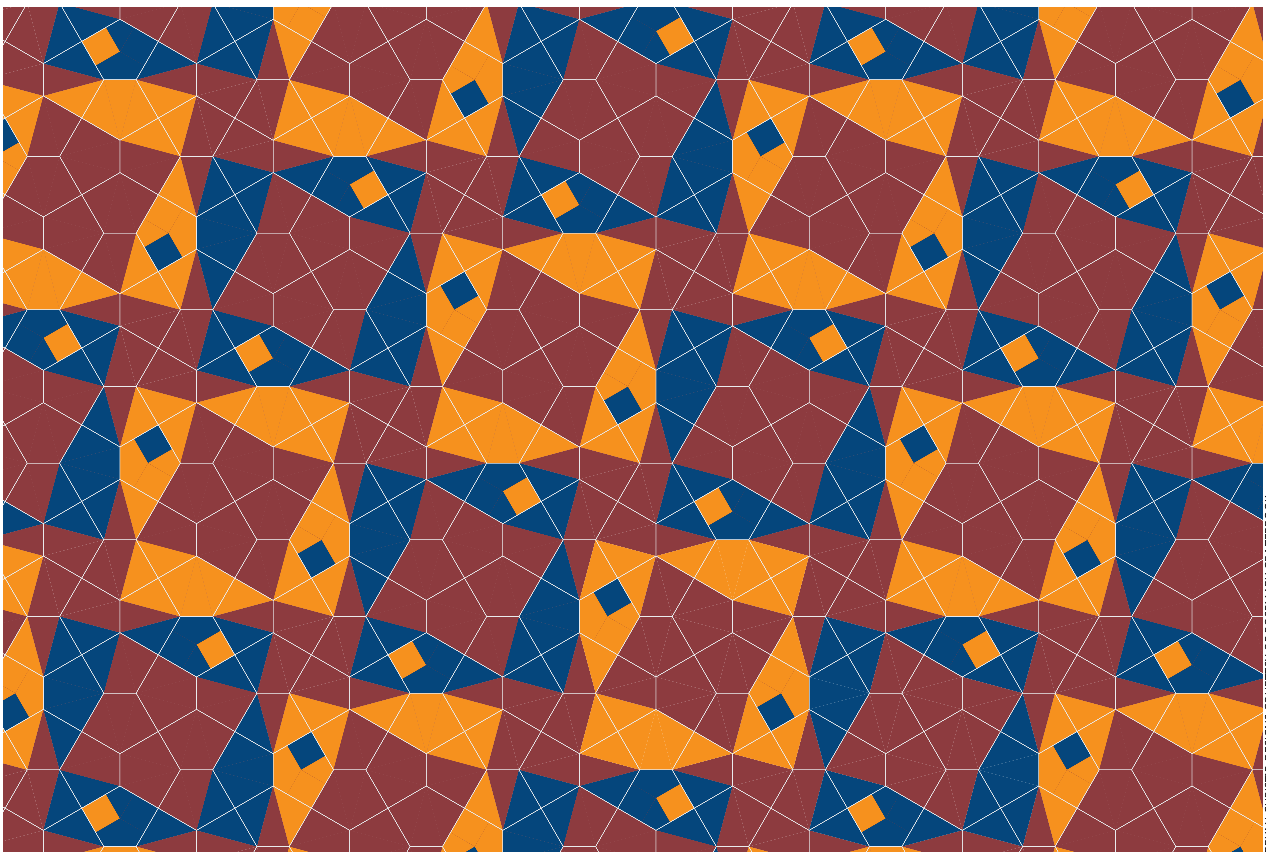
The lattice condition is less natural for tiles, which are made individually, but it is an easy scheme for an artist to follow when placing them on a wall or a floor. The square bathroom-tile lattice, for example, has rotational symmetries through 90 degrees. It also has reflectional symmetries about vertical, horizontal and diagonal lines that pass through the center or vertex of each tile or through the midpoint of each tile edge. A "honeycomb" tiling by regular hexagons is also a lattice, but it has different symmetries, notably rotations through 60 degrees. For a more detailed discussion of lattice patterns, see *Symmetry in Chaos,* by Michael Field and Martin Golubitsky (Oxford University Press, 1992).

Grazebrook discovered that a partic-

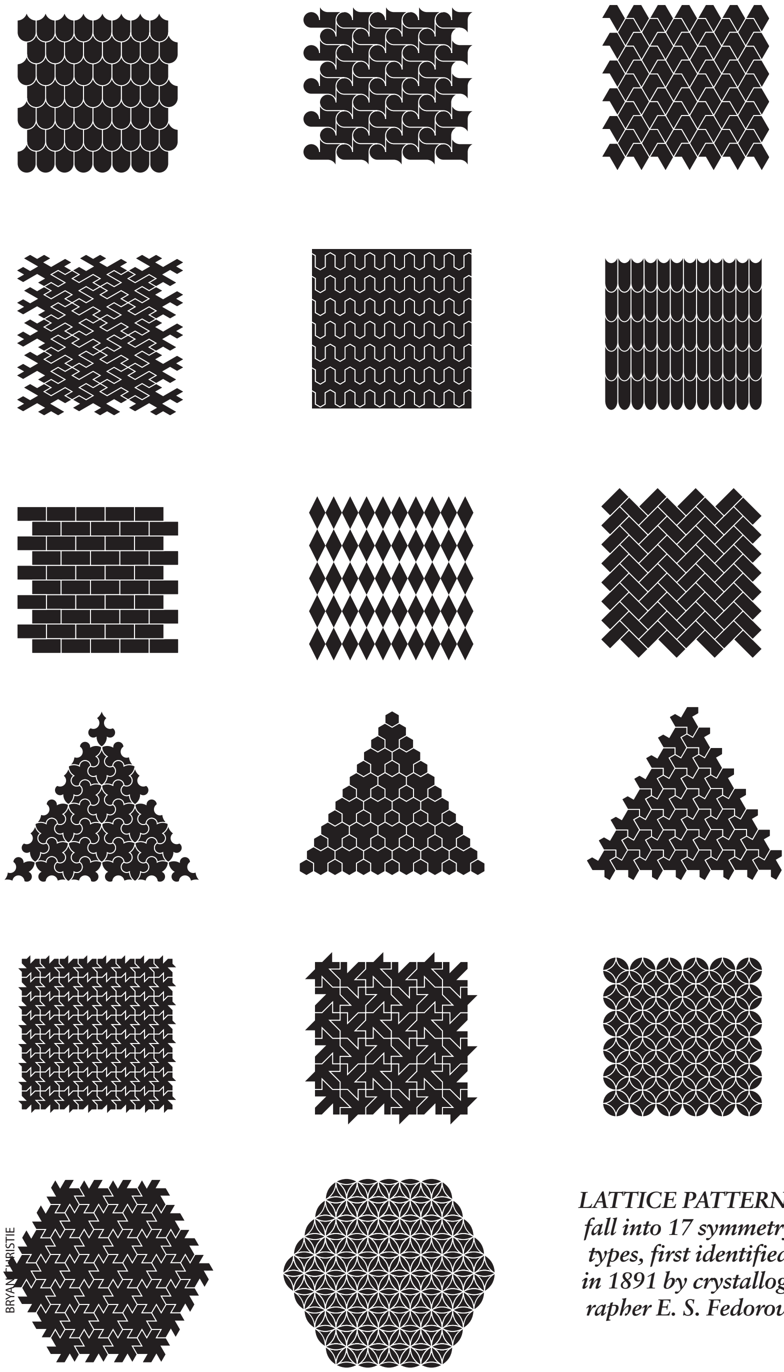


BRYAN CHRISTIE

PENTAGONAL TILES,
colored in the patterns shown above, can form a lattice tiling in conjunction with regular hexagons **(opposite page, top)** ***or by themselves*** **(opposite page, bottom).**



BRYAN CHRISTIE; DESIGNS COURTESY OF ROSEMARY GRAZEBROOK



BRYAN CHRISTIE

LATTICE PATTERNS fall into 17 symmetry types, first identified in 1891 by crystallographer E. S. Fedorov.

ular pentagonal tile can be the building block of a multitude of lattice patterns. A key feature of the tile is that it has two angles of 90 degrees and three of 120 degrees, allowing the tiles to be arranged in both square and hexagonal lattices [*see illustration on preceding page*]. A square tile, in contrast, has only 90-degree angles, so it can form just a few distinct lattices. Four of Grazebrook's pentagonal tiles can be fitted together to make a wide, short hexagon, which tiles the plane like bricks in a wall. When the pentagonal tiles are augmented with regular hexagons, they can form all but one of the 17 symmetry types of lattice patterns. (I leave readers the pleasure of discovering which is the missing symmetry type and how to obtain the other 16.)

Grazebrook first got the idea for these tiles from this very column—or, more accurately, from its predecessor, Martin Gardner's inimitable Mathematical Games column. She was studying for a Ph.D. at London's Royal College of Art, focusing on the Islamic art at the Alhambra. She started a dissertation entitled "From Islam to Escher and Onwards ...". (Readers are probably familiar with the remarkable drawings of M. C. Escher, many of which use animal shapes as tiles, arranged in mathematical patterns.) Grazebrook sensed a connection between Islamic art and Escher's characteristic tiling patterns, but only after reading Gardner's column did she realize that the link is the theory of the 17 lattice symmetry types. From that point on, she began to explore ways to make Islamic patterns using various lattice-based grids.

Grazebrook introduced two distinct schemes for coloring her pentagonal tiles. One scheme divides the tile into three triangles: this is called the "Pentland" set. The other coloring scheme divides the pentagon into four regions: two squares, one kite-shaped quadrilateral and a smaller pentagon. This is the "Penthouse" set. Of course, it is possible to divide and color the tiles in many other ways, but these sets alone can form an amazing variety of designs. The designs shown on the preceding page are copyrighted, and the coloring schemes are registered. To inquire about the rights for their use, tile manufacturers can contact Grazebrook at P. O. Box 328 ISLEWORTH, TW7 6FB, U.K. S

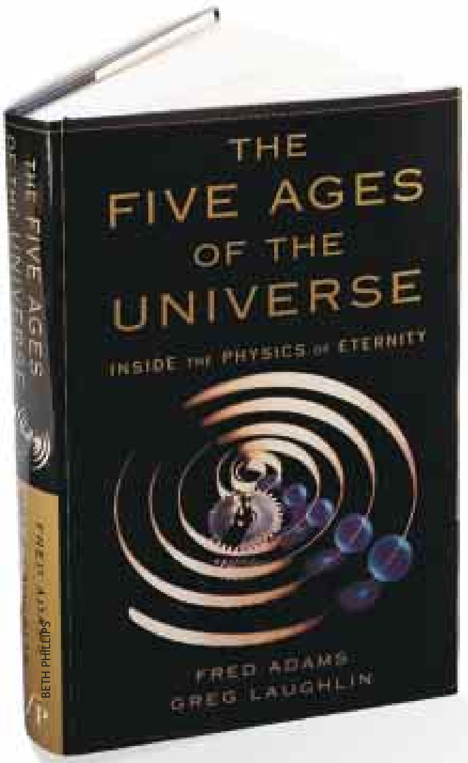
FEEDBACK

The column on coin tosses and dice ["Repealing the Law of Averages," April 1998] attracted the attention of Tom Guldbrandsen of Lyngby, Denmark. Suppose you keep rolling a die and observe the number of rolls that result in 1, 2, 3, 4, 5 or 6. What is the probability that at some stage all six totals are the same? Guldbrandsen noted that this event can happen only on rolls 6, 12, 18 and so on—multiples of 6. He found a formula for the probability that on roll 6*n* the totals are all equal. Taking account of the possibility that they may be equal more than once, he concluded that the probability is 0.021903735824 (to 12 decimal places). The analogous result for a five-sided die is 0.06469, for a four-sided die is 0.2035 and for a three-sided die is 1. *—I.S.*

AN ARMCHAIR JOURNEY TO THE END OF TIME

Review by Neil de Grasse Tyson

The Five Ages of the Universe: Inside the Physics of Eternity
BY FRED ADAMS AND GREG LAUGHLIN
Free Press, 1999 ($25)



BETH PHILLIPS

Imagine peering into a crystal ball and watching the laws of nature run their course through all of time and all of space. What exactly would you see? One thing is for sure, the cosmos is destined to expand forever. Regardless of what you may occasionally hear on the street or read in the newspapers, the idea that the universe will one day recollapse has never been supported by reliable data. We've made the observations. We've done the arithmetic. When you add up all the mass contained in the hundred billion galaxies scattered from here to the limits of our most powerful telescopes—the ubiquitous dark matter included—you do not have enough gravity to halt our current state of expansion. Worse yet, recent evidence that compared the observed brightness of distant supernovae with their predicted brightness suggests that the expansion of the universe may actually be accelerating.

This one-way cosmos in which we live may not be philosophically satisfying, but to Fred Adams and Greg Laughlin, co-authors of *The Five Ages of the Universe,* it's a theorist's amusement park. Armed with just the few basic laws of physics and an understanding of the astrophysical behavior of cosmic objects, the authors ride the universe into a formerly unimaginable future. Making the necessary assumption that our knowledge of the laws of physics is accurate and complete, they ask a simple question of their crystal ball: What is the long-term evolutionary fate of all objects in our eternally expanding universe, from its subatomic particles to entire galaxies?

Their answer takes the reader so far into the future that the ordinary reckoning of time swiftly loses its utility. So they use a sensible new clock wherein each tick η (the Greek letter eta) is a cosmological "decade" that lasts 10 times longer than the previous tick. In other words, they reckon time by the exponent when years are measured as a power of 10. A logarithmic timescale is entirely appropriate because the pace of events slows down over time: unimaginably brief intervals in the early universe saw as much astrophysical action as stretches of billions of years do today.

Having anointed themselves with powers of hindsight and foresight, the authors move from the big bang to the indefinite future, characterizing the universe along the way by five basic time periods. First comes the primordial era ($-50 < \eta < 5$), followed by the stellar era ($6 < \eta < 14$). Next is the degenerate era ($15 < \eta < 39$), in which the authors assure us that the name refers to a dense quantum state of bulk matter rather than a state of moral turpitude. The black hole era ($40 < \eta < 100$) follows, and of course they end with the dark era ($\eta > 101$). For reference, the current 15-billion-year age of the universe can be written as 1.5×10^{10} years and falls just above $\eta = 10$.

Yes, we live in the stellar era, where the energy generated within the universe is dominated by starlight. The stellar era also happens to be when all our laws of physics were discovered and tested, so this part of the book will certainly have the longest shelf life. The contents of both the primordial and stellar eras may ring familiar to avid readers of popular literature on astronomy, but the treatment nonetheless represents a compact, if occasionally dry, review of modern astrophysics.

Decay and Degeneration

At the dawn of the degenerate era, all gas clouds have been used up to make stars. All stars, even the "long-lived," low-mass ones, have exhausted their thermonuclear fuel. All that's left is the trinity of degenerate stellar corpses: white dwarfs, neutron stars and black holes.

By the middle of the degenerate era, a single cosmic decade lasts 25 powers of 10 longer than the current age of our universe. Predictions get more and more speculative and more and more fun, because events that were formerly improbable in one decade now become highly likely in another decade. In the stellar era, stars hardly ever journeyed near enough to one another for their gravity to make a substantial difference in their orbital paths, even during head-on collisions of entire galaxies—stars are very small when compared with the distances that separate them. The stars (rather, their corpses) now have close encounters almost continuously and thus undergo "dynamical relaxation," in which low-mass objects are thrust out of the system while high-mass stars descend toward the galaxy center.

While some corpses are cast adrift in the cosmos, the rest of them are eaten whole by the supermassive black holes that lurk in the galactic centers. We have entered the black hole era, where nearly all cosmic energy is now traceable to Hawking radiation as the black holes of the universe evaporate away. When all black holes have disappeared, and there are no sources of fresh energy left, we have entered the dark ages: the temperature of the entire universe asymptotically approaches absolute zero. Only then will the cosmos be dead, by any measure of the word.

Adams and Laughlin deftly invoke all known laws of the universe to spin an entertainingly scary picture of our distant future.

The authors' journey through time continuously engages the imagination as they take the known laws of physics right up to their natural limits. In this intellectual venue, speculation can be justly accused of becoming wishful thinking. Yet sometimes wishes come true. Cosmologists have been describing the early universe ever since physicist George Gamow, in the 1940s, turned the clocks back and predicted the existence of remnant energy from the big bang—the cosmic microwave background radiation.

And today, for example, grand unification theories in physics predict that the proton is unstable and will eventually decay in 10^{30} years—a factor of a quintillion longer than the current age of the universe. Experiments are now being designed to see this happen. Naturally, proton decay factors significantly into the happenings of the degenerate era, as the authors are granted plenty of time to kill every proton in every nucleus of every atom in the entire universe.

In *The Five Ages of the Universe,* Adams, who teaches physics at the University of Michigan, and Laughlin, a postdoctoral fellow at the University of California at Berkeley, deftly invoke all known laws of the universe to spin an entertainingly scary picture of our distant future. During our eternal cosmic expansion, if new laws of physics are revealed, then many (if not most) of their predictions will fail. They admit this obvious shortcoming. But I don't mind, because I enjoyed the journey. When new laws of physics demand it, I will simply ask them to weave an updated scientific tale that takes me back to the future once more.

NEIL DE GRASSE TYSON is the director of the Hayden Planetarium at the American Museum of Natural History in New York City. He is the author, most recently, of Just Visiting This Planet *(Doubleday, 1998).*

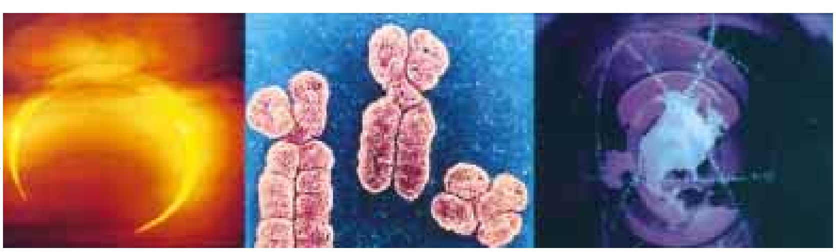
THE EDITORS RECOMMEND

ONE RENEGADE CELL: THE QUEST FOR THE ORIGINS OF CANCER. Robert Weinberg. Basic Books, New York, 1998 ($21).

This is the cancer story, told with care and clarity and unfolding like a good detective novel. Skilled detective work is what it has taken to determine the causes and nature of the disease and to bring medical science to a time when it is becoming increasingly possible to prevent or treat cancers. Weinberg, professor of biology at the Massachusetts Institute of Technology and a founding member of the nearby Whitehead Institute for Biomedical Research, is prominent among the detectives. His account starts with the single "renegade cell" that begins an uncontrolled growth in one of the body's tissues, eventually giving rise to a cancerous tumor. But his main focus is on the findings of the past two decades that have yielded an understanding of the disease—among them the role of carcinogens and viruses and the discovery of oncogenes, growth factors and the cell cycle clock. "We have learned much about the invisible forces that create human cancer," he writes. "Knowing the causes of many tumors, we should be able to prevent their appearance, or if they appear, to treat them and achieve permanent cures."

THE SUN, THE GENOME, AND THE INTERNET: TOOLS OF SCIENTIFIC REVOLUTIONS. Freeman J. Dyson. Oxford University Press, New York, 1999 ($22).

Dyson, who gained eminence in physics at the Institute for Advanced Study, is also sure-footed in other areas of science and in examining the social implications of scientific achievements. He displays all those talents in this book, which is based on lectures he gave at the New York Public Library in 1997 "to show to an audience of nonscientists how science could be important in their lives." His aim in the book is to suggest developments that might be significant in the 21st century and to show how, "either along this road that I describe, or more probably along some other road, we have a chance to reach a happier and more equitable world." The major developments he foresees are in genetic engineering, the Internet and solar energy. He discusses these and many related subjects in his characteristically limpid prose. "I am looking," he writes, "for ways in which technology may contribute to social justice, to the alleviation of differences between rich and poor, to the preservation of the earth."



FROM THE SUN, THE GENOME, AND THE INTERNET

FINDING THE WALLS OF TROY: FRANK CALVERT AND HEINRICH SCHLIEMANN AT HISARLIK. Susan Heuck Allen. University of California Press, Berkeley, 1999 ($35).

Received wisdom has it that Heinrich Schliemann, a German businessman turned archaeologist, discovered the remains of ancient Troy at Hisarlik in modern Turkey in 1868. That tradition, according to Allen (visiting scholar and guest lecturer in the classics department at Brown University and visiting lecturer at Smith College), arises from Schliemann's self-promotional writings. "But there is another claim to be staked," she writes, "both to some of Schliemann's treasures and to the honor of actually having found the site of Troy. That claim belongs to the man who owned half the land on which Troy eventually was found, the man who informed and educated Heinrich Schliemann about the site and persuaded him to dig there."

That man was Frank Calvert, an Englishman who served for 34 years as a U.S. consular agent at the Dardanelles, all the while steeping himself in Trojan archaeology. Allen describes the contributions of Schliemann and Calvert to the Troy work and brings the story of archaeological activity at the site up to the present, illustrating the tale with many maps, photographs and drawings. Calvert's role has been obscured, she says, because—in contrast to Schliemann—he was "a self-effacing, private person," and "only the occasional letter offers details of his unpublished achievements, the manuscripts for which rarely have been found."

The Hunting Apes: Meat Eating and the Origins of Human Behavior. Craig B. Stanford. Princeton University Press, 1999 ($24.95).

Eight hunters in East Africa, followed by Stanford, have had a good day. They sit about, feasting on the meat, and they "politick throughout the meal" over ways of sharing the catch. Members of a hunter-gatherer group? No, chimpanzees. "I argue that the origins of human intelligence are


FROM THE HUNTING APES

linked to the acquisition of meat, especially through the cognitive capacities necessary for the strategic sharing of meat with fellow group members," Stanford writes.

Stanford, who is associate professor of anthropology at the University of Southern California, sees meat "not only as a nutritionally desirable food item but also as a social currency that is controlled by males and therefore is a tool for the maintenance of patriarchal systems." He discusses the residual effects of this heritage in human societies, thereby risking attack from feminists. His main focus, however, is on what meat sharing by our primate ancestors meant for human intelligence: "The intellect required to be a clever, strategic, and mindful sharer of meat is the essential recipe that led to the expansion of the human brain."

The Ostrich Factor: Our Population Myopia. Garrett Hardin. Oxford University Press, New York, 1998 ($22).

The ostriches Hardin sees are the people who think that continued growth of the human population is no problem—even a good thing. "Perpetual growth has become a secular religion built on the assumption that *growth = progress*." Hardin (professor emeritus of human ecology at the University of California at Santa Barbara) thinks population growth is definitely a problem. Finite resources, he holds, cannot support infinite growth. "Ask yourself this question: what features of your daily life do you expect to be *improved* by a further increase in population?" Hardin tends to shout and wave from his pulpit, and he acknowledges that most of his argument will be "abhorrent to large numbers of Americans (as well as to many other modern people)." But his challenges to widely held assumptions are bound to stir the reader's thoughts and probably emotions.

Skywatchers, Shamans & Kings: Astronomy and the Archeology of Power. E. C. Krupp. John Wiley & Sons, New York, 1999 ($17.95).

"Through calendar, ritual, symbol, and myth, shamans, chiefs, and kings invest the landscape with magical power from the meaning they extract from the sky. Through such transfers of power, they guide and govern the lives of those who reside on earth." That is the way it was in ancient societies, says Krupp, an astronomer who directs the Griffith Observatory in Los Angeles. His interest in the connection between astronomy and earthly power has led him to visit more than 1,300 sites where relics of reliance on celestial signs remain. In this book (a paperback edition of the 1997 hardback), he takes the reader to many of the sites and provides numerous photographs of what one sees there. And although social structures no longer rest on what people see in the stars, he says, belief in the miraculous lingers on, as evidenced by tales of flying saucers and sightings of Elvis.

The Illusion of Orderly Progress. Barbara P. Norfleet. Alfred A. Knopf, New York, 1999 ($20).

It is a slender book of stunning photographs, part serious science and part whimsy. Norfleet has posed many colorful insects, most of them dead, in more or less natural settings and photographed them. She presents a five-inch by seven-inch photograph on each right-hand page. The whimsy is in the brief caption on each facing page and often in the related photograph. For example, the caption that also serves as the book's title accompanies a photograph of 13 shining leaf chafer beetles (*Chrysina macropus*) forming a vertical triangle around a piece of clay in what appears to be almost military precision, but they are in fact circling forever and

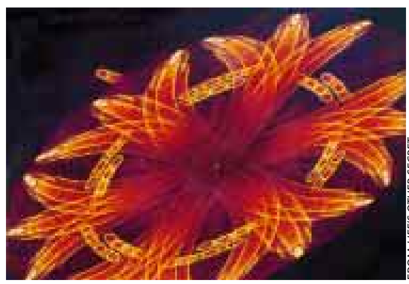

FROM THE ILLUSION OF ORDERLY PROGRESS

going nowhere. At the end of the book, Norfleet identifies the insects in each photograph insofar as their identity is known. "There exist between 10 and 30 million insects," she notes, "and only about 1 million have names." Norfleet is founder, director and curator of the photography collection at Harvard University's Carpenter Center for the Visual Arts. She has done herself proud with this, her seventh book.

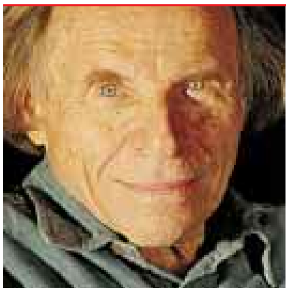
Life's Other Secret: The New Mathematics of the Living World. Ian Stewart. John Wiley & Sons, New York, 1998 ($16.95).

Life's first secret, Stewart says, is the molecular structure of DNA. The other secret, he believes, is mathematical control of a growing organism. (Mathematician Stewart's activities include conducting this magazine's Mathematical Recreations department.) Arguing that "life is a partnership between genes and mathematics," he embarks on an absorbing study of what life is, how it originated and how the search for mathematical laws that underlie the behavior of living organisms will illuminate those deep questions.

Along the way, he examines mathematical patterns in flowers, bird feathers, animal locomotion and many other features of life. But he hopes for much more profound findings in biomathematics. "A full understanding of life depends on mathematics," he writes. "At every level of scale, from molecules to ecosystems, we find mathematical patterns in innumerable aspects of life. It is time we put the mathematics and the biology together."


FROM LIFE'S OTHER SECRET

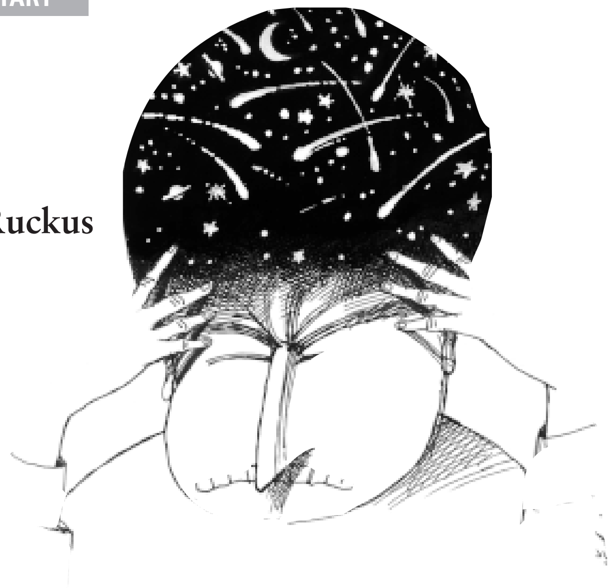
COMMENTARY



WONDERS

by Philip Morrison

The Hidden Cosmic Ruckus



DUSAN PETRICIC

The sun and its planets share the universality of the building blocks of our quantum world: electrons, nucleons and photons. But it comes as a bit of a surprise that the solar system and distant planetary systems have another distinctive modular origin all their own. Those planetary "bricks" are not tiny identical particles; rather they are roughly built out of dust, rock, tarry organics and ice, somewhat like a Boston street gutter in winter. They were postulated around 1900 by two University of Chicago professors, geologist T. C. Chamberlain and astronomer F. R. Moulton. The fine old word "infinitesimal" had long expressed a vanishingly small quantity, so they coined "planetesimal"—the smallest object that might be thought of as an orbiting planet.

In abundance, such modules of matter—estimated to be about a mile in diameter—will attract, collide and merge to become progenitors of full-scale planets. As planetesimals grow ever more massive, their gravitational attraction to the sun and to one another becomes more effective than the collisions they encounter as they move in the solar nebula.

Here a savvy reader might well object. If a final Earth sphere is to be formed by the merger of many planetesimals, it will require 10,000 of them aligned along each of the three dimensions—the length, the depth and the width—amounting thus to about one trillion planetesimals. A few more numbers may serve to orient. The cosmic space we can survey offers us a view of fewer than a trillion galaxies and of fewer than half a trillion stars that make up our own galaxy. Our human cohort numbers only six billion heads; even the census of all our ancestors summed up over the entire history of our species amounts to a tenth of one trillion.

Can we grant so bold a postulate, at once invoking trillions of unseen planetesimal modules? Should not old Occam's razor cut them off, as fine specimens of hypothetical "entities multiplied beyond necessity"? We certainly should—*except* that we have evidence for trillions of their counterparts even today.

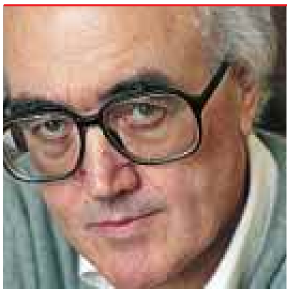
Comets arrive nearby after falling in as far as a light-year to approach the sun. New comets have straggled sunward from remote darkness every year for five billion years. In itself that would imply tens of billions stored, thereby allowing for losses. Long study of the orbits of comets shows that the gravitational disturbances from passing stars and clouds of gas only rarely nudge a comet out of the cold attic, so the original comet inventory must rise to many trillions. That comets come in trillions verifies the planetesimal idea, for comets are but a species of planetesimal from uncrowded icy orbits. The densely pockmarked faces of the moon and the airless planets, moreover, record the waning barrage that closed the curtain on planet formation, a process that is now all but extinct.

Has our well-ordered solar system grown orderly merely by aging?

Accept that trillions of mile-size chunks formed in plenty, growing from gas and grains through sticky collisions, at best tentatively understood. The chemistry of contact as binding agent gradually gave way to gravitation as the objects grew. Planetesimals can interact without contact. Slowly their orbits simplify as countless gravitational energy transfers space out, circularize and flatten the initial thick-braided cloud of orbits. Planetesimal collisions flourish; some partners chip; more cohere by gravity. Eventually, large composites aggregate out of the pell-mell collisions, until at last the biggest runaway clumps sweep up most residual surrounding orbiters unto themselves. Simulations of this sequence by powerful computations yield a result resembling the solar present, where well-spaced planets revolve in near-circles within a thin, flat disk amid a complex but dilute cloud of lesser bodies.

Although gravity is indifferent to the chemical composition of matter, chemical bonds determine many features of the planets. Where close-in planetesimals feel the sun's heat, few will be icy; far out, ice (the most common of molecular solids) will dominate, and the rest will be mere contaminants. Close in there is less room, and collisions will be fast and furious. Far away, space is ampler, and slower orbital collisions will be less frequent. Thus, comets mostly remain icy individuals. The cool region of massive Jupiter and its gas giant kin lies between; there ice and gas abound, and strong planetary gravity can even hold on to the free helium and

Continued on page 106

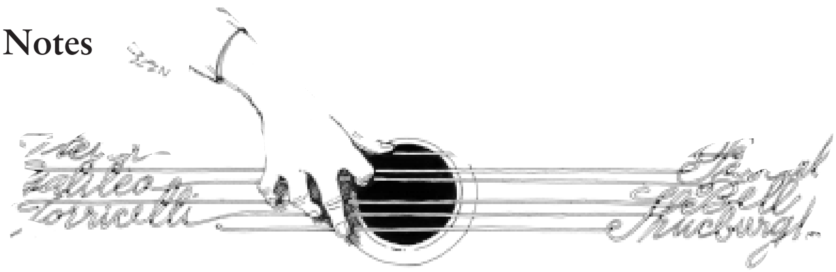


COMMENTARY

CONNECTIONS

by James Burke

A Few Notes



DUSAN PETRICIC

One of the things I do to relax (it has the opposite effect on all within earshot) is to play the classical guitar badly, and the other day I warmed up by accompanying myself to a whistled rendition of "Yankee Doodle." Then, just as I was getting down to the serious matter of scales, before attempting yet another failed attack on "Recuerdos de la Alhambra," it flashed upon my inward eye that scales had been mathematically sorted out by that Dutch Renaissance whiz Simon Stevin. Pioneer of decimal fractions, military adviser to Count Maurice of Nassau and builder of sand-yachts. And he who had divided the octave into the semitones I was now plucking.

In 1608 Stevin must have been out to lunch on the day an unknown local optical noodler named Hans Lippershey fetched up at Maurice's place with a new gizmo to help the count in his never-ending efforts to turn the Dutch army into a high-tech force with which to chuck out the occupying Spaniards (which he eventually did). Lippershey brought along a tube with a lens at each end to be used for "looking," as he put it. Maurice is reported to have muttered something about binoculars and sent him off with a flea in his ear. Next thing we hear, it's 1609, and Galileo's got the kit and built one. He is about to change the entire history of everything by revealing that the moon has mountains. And he will go on to prove that Earth isn't the center of the cosmos by showing moons orbiting some other body: the planet Jupiter.

The solar system concept was what Copernicus had been clobbered for nearly 100 years earlier, so surprise, surprise—much the same was about to happen to the big G. One of the other crimes Galileo was also to commit (and which was almost as bad as heliocentricity) was to encourage researchers to do something about nothing. As in the vacuum. Which was not supposed to exist, because any empty bits of the universe were reckoned to be filled by God's presence. It started in 1630, when Galileo was approached on the problem of why suction pumps would not lift water more than about 30 feet. A weighty matter when you were digging wells for water to power ducal fountains in Florence. Galileo kind of passed the puzzle on to one of his acolytes, Evangelista Torricelli (who lived in Galileo's house during the last years of his life and would end up succeeding him as mathematician and philosopher to the duke of Tuscany).

Subsequent Torricellian thoughts led to a column of mercury in a tube being upended in a dish of mercury. During upending, some of the mercury in the tube ran out into the dish, but some remained in the form of a column reaching almost all the way up the tube. The gap above the almost? The impossible and, as you know, heretical vacuum. Over a number of days, Torricelli noticed that the level of the mercury in the tube crept up and down. Had this to do with changing air pressure on the surface of the mercury in the dish supporting the column of mercury in the tube?

A copy of a secret letter about this risky idea, sent by Torricelli to a Roman propeller-head pal named Michelangelo Ricci, got into the hands of the only person who was likely to be able to do anything about it. This was Marin Mersenne, a scientific priest in Paris with the biggest address book in Europe. Mersenne was one of those guys who might not know the answer to something but always knew a man who did. In this case, that someone was going to have to find a glass factory, one of the essentials of vacuum experimental gear being long glass tubes. This was high-end stuff, not readily available back then in your neighborhood mall. Unless you lived among the glassmakers of Rouen, which this fellow did.

Galileo encouraged researchers to do something about nothing—as in the vacuum.

Then came the ticklish matter of mountains. Rouen is pancake-flat, and this chap wanted to take the mercury in the tube up a significant height to see if upness meant lower air pressure and a fall in the level of the column. Fortunately, the city of Clermont-Ferrand in central France had both mountains and his willing and able brother-in-law, name of François Périer. On September 19, 1648, Périer visited the peak of Puy de Dôme and went up and down. And so did the height of his mercury column, making like a barometer. And clinching the reputation of the fellow who had put him up to it all (4,888 feet up, to be exact): his brother-in-law, Blaise Pascal.

Pascal was a mathematical genius who designed the first working calculator and was deeply into gambling and probability. Which may be why he was also in deep doo-doo with Rome over his links with radical back-to-basics Catholic reformers known as Jansenists. These types, followers of Dutch priest Cornelius Jansen, attacked Jesuits for their probabilism ("what you're thinking about is probably not a sin if a church authority says not"). Jansenists, *au contraire,* were for probabiliorism ("you never know—it's more probable to be a sin than not, so don't do it").

Now, back then, criticizing power-of-thumbscrew Jesuits was a good way to get yourself taken seriously dead. By 1705 a Papal bull required Jansenist priests and nuns to get out of the habit, or to get out of the habit. Which is just what happened to Father Michel de L'Épée, who ended up in Paris, opening a school where he taught sign language to the deaf and mute. Did the job so well that in a test one of his star pupils was able to answer 200 questions in three languages. By 1789 the school head was Roch-Ambroise Sicard, who finished the dictionary of signs L'Épée had started.

In 1815 an American, Thomas Gallaudet, turned up to learn the teaching technique. Two years later he had established the Connecticut Asylum for the Deaf and Dumb in Hartford. In 1872 a Scottish immigrant did a two-month teaching stint at the asylum and then became a professor of vocal physiology at Boston University. It was there, while trying to develop a system to help deaf people to "feel" or "see" sounds so as to imitate them, that the prof took a close look at how the eardrum worked and persevered in finding a way to make a vibrating membrane generate a vibrating electric current that would in turn vibrate another membrane. We call the resultant contraption that Professor Alexander Graham Bell came up with: the telephone. Because Bell was less than qualified to do any of the electrics involved, he wisely took advice from eminent science guru and Smithsonian secretary Joseph Henry.

At one point early in his working life, Henry had been a tutor in the household of the Van Rensselaers, the Dutch patroon family that owned much of New York State from the 17th century. In 1642 in the city of Rensselaer on the Hudson River, just across from the family home, Fort Crailo was built to protect the settlers. Tradition has it that it was in this fort that an English medic, Richard Shuckburgh, composed the tune I was whistling at the start of this column.

Oh, well. Back to my scales.

Wonders, *continued from page 104*

hydrogen atoms that escape little Earth.

The planets began as cold accumulations of solid planetesimals. Their atmospheres are at the surface (or escaped entirely). H_2O, if present, is mainly below. Oxidized rocks are deeper still, then a thick mantle, and deepest down is a dense iron core that must once have rained down from molten slag to collect at the center, just as in a furnace! The clues pointing to the inner planets' fiery origin are too strong to deny and are supported by detailed study. But of course, the icy planetesimals themselves can kindle and fuel that furnace, if only they cohere rapidly enough. The kinetic energy they bring in by collisions is enough to melt an Earth or a Venus, probably again and again in repeated stages over a few million years. The births of the big boys (Jupiter is as massive as 300 Earths) are less well understood—they may be largely the results of gas accumulations, because they are mostly hydrogen and helium. Or perhaps they are composites, starting out as icier, planetesimal-built cores but capacious enough to draw in cold gas to fill out their bulk. Remember that the main ingredients of the sun and its nebula are hydrogen and helium, more than 98 percent of all the atoms it has.

Has our well-ordered solar system grown orderly merely by aging? Many planets may have come and gone, merged into the sun or out into space, like the gases lost earlier from the sun-forming molecular cloud. The wonderful newly found distant systems show us many "hot Jupiters." We do not now see how those could form so near their star. It is more plausible that they arose in an outer cool zone, then migrated inward under gravitational interactions, tidally with the star, with nebular remnants or even with a massy rival planet.

Our sketchy idea of planetary origins is about as secure as that of a botanist who would infer a life history from one blossom, the only flower he had ever seen. But at last we are on the way to an enlightening variety of planetary specimens. Someday we may detect signs of distant planet formation under way: a pelting storm of planetesimals, a star engulfing whole planets, even giant planets in collision. Can such a ruckus remain forever hidden?

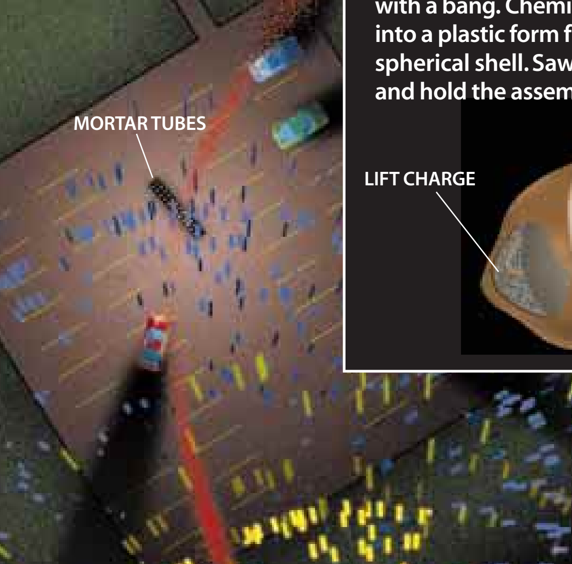
WORKING KNOWLEDGE

AERIAL FIREWORKS

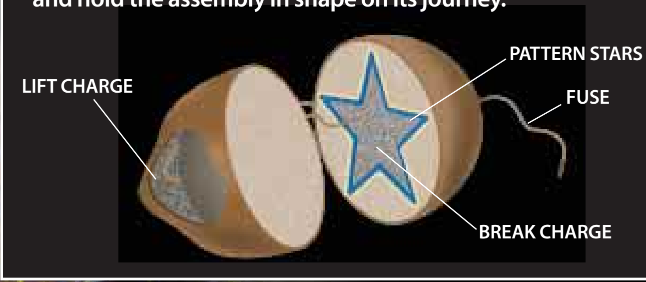
by George R. Zambelli, Sr.
President, Zambelli Fireworks

Surely no other area of applied chemistry has given people so much wonder and enjoyment as fireworks have. Modern displays use computer-controlled electronic ignition and precisely timed fuses to synchronize the bursts to the pulse of music. But the spectacular explosions themselves result from the arrangement of powders, resins, gums, paper and string in clever (and often secret) ways that have changed remarkably little despite five centuries of pyrotechnical experimentation.

MORTAR TUBES made of metal or polyvinyl chloride (PVC) plastic are sunk into the ground and loaded with shells before the show. A long fuse rises out of the tube to connect a pouch of explosive black powder—up to six ounces of it for a three-stage shell six inches in diameter—to an electronic "squib" that ignites the lift charge under computer control.

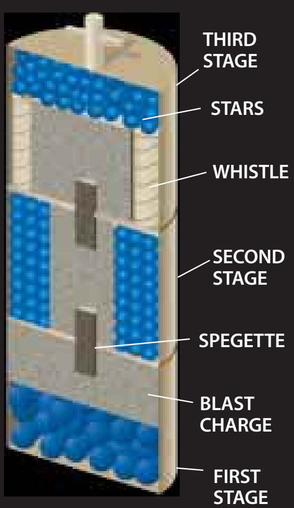


FIERY FIVE-POINTED STAR, heart or peace symbol erupts with a bang. Chemical pellets called stars, which are packed into a plastic form filled with blast powder, explode out of a spherical shell. Sawdust or rice hulls fill the rest of the shell and hold the assembly in shape on its journey.



WHISTLING FIREWORKS include cardboard tubes inside the shell that are packed with potassium perchlorate, red gum and sodium salicylate and plugged with clay at one end. As the composition burns, the gas it emits creates a high-pitched whistle.

SINGLE SIX-INCH SHELL may have several "breaks," or distinct bursts, as it rises to a peak of several hundred feet. Hard tubes packed with powder, known as spegette fuses, pass the fire from one break to the next. By varying the amount of powder in the spegette, designers can precisely adjust the delay between breaks from one to eight seconds.



BLAST CHARGE inside the shell ignites spherical "stars" rolled from powdered metals, salts and adhesives. The burning stars can flicker or change in color as one layer vaporizes and exposes another of different composition.

SLIM FILMS/BRYAN CHRISTIE