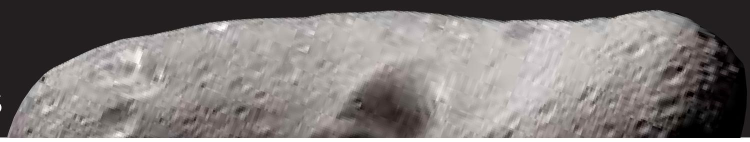
Asteroid Hopping

surprising answers from the first close-up images



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SPECIAL REPORT:

HARD-DISK CRASH?

How IBM, Seagate, HP and others will prevent the coming memory crisis

Metallic Hydrogen

The Stuff of Jupiter's Core Might Fuel Fusion Reactors

AIDS in Africa

Fighting to change behaviors that spread the plague

Crowd Pleasers

How we keep the peace when space gets tight

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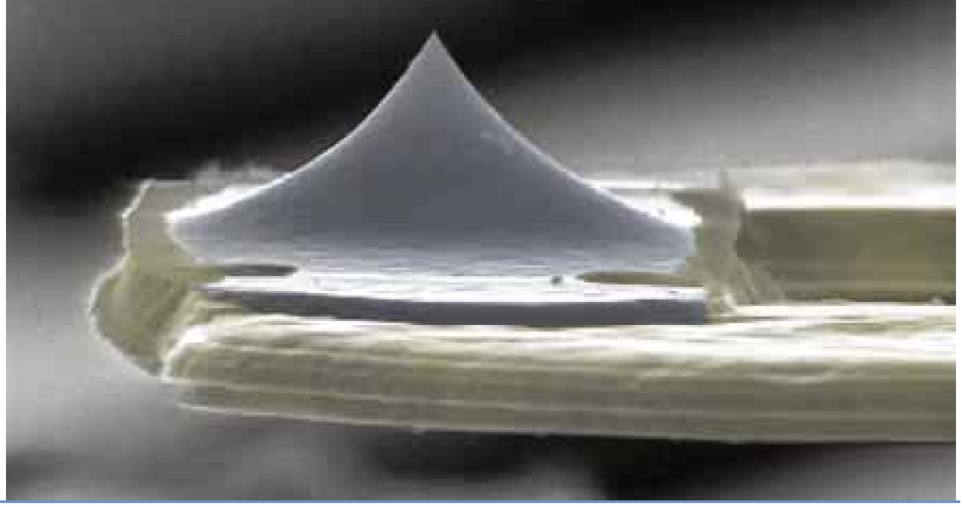

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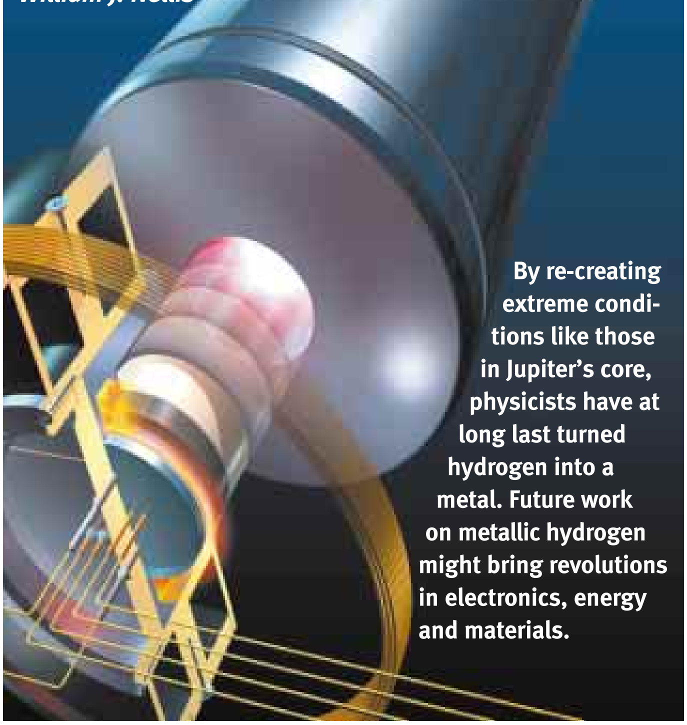

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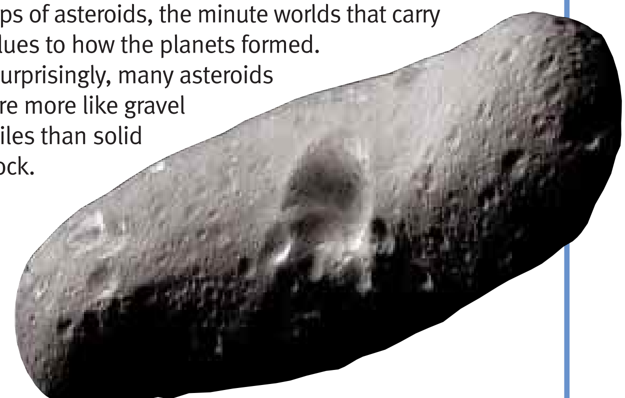

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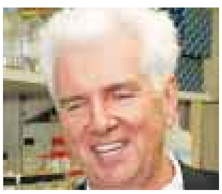

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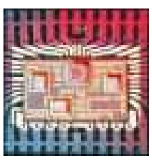

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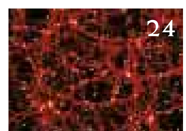

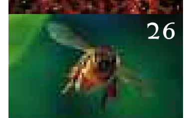

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Image by Bryan Christie.

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EDITOR_CAROL EZZELL

Africa's Suffering

Covering AIDS in Africa is like watching mass murder in slow motion, so I probably didn't maintain enough professional objectivity for my own good. As a science writer, I don't have to wear emotional armor very often. Before I went to Zimbabwe for the article beginning on page 96, I had talked to other reporters who had spent time in Africa. All told me to brace myself for the orphans—many of whom had contracted the AIDS virus from their mothers—and the strong, futile desire to make everything all right for them.

Carol Ezzell helping Musafare Bunu in the AIDS hospice Mashambanzou.

Then again, nothing could have prepared me for the visit to a crèche for AIDS orphans in Harare, where one sick, smiling four-year-old boy tried to keep up with the other kids playing ring-around-the-rosy but was so weak he kept slumping to the floor. Or meeting a 25-year-old unmarried girl who cares for her two-year-old nephew even though her only income is from growing and selling a few vegetables at the local market. The boy is the son of a married man who impregnated her young sister and gave her AIDS and who now will not acknowledge his son. The boy, who calls his aunt "Mama," was too listless even to take the piece of banana I offered.

As a science writer, I don't have to wear emotional armor very often.

During one interview at a hospice called Mashambanzou in the Harare suburbs, a bedridden woman watched me silently, her mouth red and swollen, her tongue white with thrush. I asked if she'd like a drink from the carafe at her bedside, and she nodded yes, too weak to move or talk. I tried to hold up her frail shoulders so she could drink out of the cup, but she winced when I lifted her. Instead I dribbled water into her parched throat as she lay back. The look in her eyes stays with me still.

Meanwhile photojournalist Karin Retief was visiting a room at the hospice where she had been told a particularly sweet orphan boy stayed. At first she did not see anyone on the bed and was about to say he must be elsewhere, when suddenly she spotted his tiny arm in the air, his body lost in the folds of the bedclothes. You can see him in the stunningly tragic photograph on page 99.

Recently Karin—who works out of Cape Town, South Africa—wrote to me that she had been able to keep our assignment from taking too great an emotional toll on her at the time. "Only when I got back, about a week later, could I mourn the people I met," she continued. "I sat in church and wanted to ask the priest to pray for the people with HIV and AIDS in Zimbabwe and all over the world. Then all the people's faces, pain and suffering became so real, I could not get the words out. I broke down and cried and cried for them."

For information on how to make donations to some of the organizations mentioned in the article that are struggling to help people with AIDS in Zimbabwe, visit *Scientific American*'s Web site (www.sciam.com/2000/0500issue/AIDS.html).

editors@sciam.com

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Scientific American, Inc.
415 Madison Avenue
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KARIN RETIEF/TRACE IMAGES/THE IMAGE WORKS

SPURIOUS SPECIES?

Ian Tattersall's article "Once We Were Not Alone" is predicated on the notion that paleoanthropologists can unequivocally identify species in the human fossil record. But the credibility of every hominid species mentioned is vigorously contested by scholars all over the world. The illusion that we can make these kinds of distinctions reliably is owed to the current popularity of cladistics, a method that uses unique, derived traits to assess genealogical links among organisms. One problem with this method in relation to the study of hominids becomes apparent, however, when we consider the large effects of sampling error in the human fossil record and the fact that we cannot claim to have representative samples of most biological populations. Such samples are necessary to rule out the possibility that what appear to be unique, derived features are not simply part of the normal range of variation within a species. In this light, cladistics becomes nothing more than an exercise in unconstrained pattern searching, uninformed by any conceptual framework, and using variables more by convention than for any demonstrable relation to the problem at hand.

It is reasonable to suppose that there were many more hominid species in the Pliocene epoch and the Lower Pleistocene than most classificatory "lumpers" would recognize, but whether the same reasoning can be applied to the Upper Pleistocene is highly questionable.

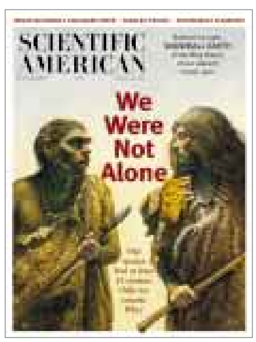
GEOFFREY A. CLARK
Department of Anthropology
Arizona State University

Tattersall replies:

Clark's letter embodies a misapprehension that has, for mystifying reasons, become widespread in some sectors of paleoanthropology. The reality is, though, that cladistics is a method of working out relationships among species and higher taxa, not of identifying those species in the first place. Species identification in the fossil record continues to pose a vexed set of problems, but paleontologists have been cheerfully addressing these since long before the advent of cladistics.

As for species diversity in human evolution, I would clearly not wish to claim that the 17 species mentioned in my article constitute a definitive number. In contrast to Clark, however, I believe that in general we will need to recognize more species as our knowledge of the human fossil record expands. Clark is certainly correct to note that not all paleoanthropologists currently agree on the distinctiveness of all those species, but to claim a contested credibility for every one of them (including such old favorites as Homo sapiens, Homo erectus *and* Australopithecus africanus*) smacks of knee-jerk reaction rather than of measured evaluation.*

THE_MAIL



A PICTURE IS WORTH at least a thousand words, but sometimes an unintended interpretation emerges. Such was the case for the illustrations in "Once We Were Not Alone," by Ian Tattersall [January]. Numerous readers questioned the absence of females in the pictures. "Out of six portraits representing various hominid species, all six feature males," observes Giovanni Dall'Orto of Milan, Italy. "This apparently male-only reality made me wonder how our ancestors reproduced." Other correspondents wondered why only *Homo sapiens* was portrayed as having light skin. "If Neandertals coexisted with moderns in Europe, wouldn't they have been blond, too?" asks Sandy Campbell of New York City.

In response, we note that to make meaningful comparisons among the different species in the available space, artist Jay Matternes had to depict members of one sex or the other, and he chose males. Moreover, females are included in the opening image and in the painting of Cro Magnons in the Tuc D'Audoubert cave. As for Neandertal skin color, there isn't any scientific consensus on this matter, but they may well have been fair, as rendered in Kate Wong's recent piece "Who Were the Neandertals?" [April]. Additional comments on Tattersall's article and others in the January issue are featured above.

SLIM FILMS; DAN WAGNER (*Times Square*); JULIA WATERLOW *Corbis* (*desert*)

WORMHOLE **might exist on a much smaller scale.**

WORMHOLES, WARP DRIVE

In "Negative Energy, Wormholes and Warp Drive," Lawrence H. Ford and Thomas A. Roman suggested that it would be possible to create a wormhole but that the wormhole would be too small to fit even a single atom through. What about a photon or, more to the point, a stream of photons? Would faster-than-light communications then be possible?

DOUGLAS PETERSON
Bloomington, Minn.

Ford and Roman reply:

This is a very good question, albeit one for which we do not have a definitive answer. There might be some practical difficulties with sending photons through a tiny wormhole. Consider the following order-of-magnitude argument: To fit through the wormhole, the photon's wavelength must be smaller than the throat size. The energy of the photon, however, is inversely proportional to its wavelength. Thus, to fit through a wormhole that is only a few orders of magnitude larger than Planck size, a photon would have to have a very tiny wavelength. The large positive energy of such a photon might disrupt the wormhole by overwhelming the negative energy, which is holding the wormhole open. But we don't know for sure, because we don't really know how to calculate the back reaction.

ELEPHANT CULLING

I read with interest "Jumbo Trouble," by Carol Ezzell [News and Analysis]. Although elephant culling in southern Africa might in the end prove necessary, there are factors that have not been adequately considered. Many species of wildlife in Africa find that habitat loss is their most serious threat as human populations expand. But First World views on conservation are seen as impractical luxuries by rural Africans whose crops and lives may be endangered by animals such as elephants.

Further complicating the issue is the fact that in Zimbabwe the accuracy of the elephant census is still not accepted by all local biologists—there may well be far fewer animals than the government statistics indicate. And because of a CITES decision that allows trade in elephant products, the reported cases of poaching in the Zambezi Valley have increased dramatically. Perhaps this is not the best time to institute a culling policy, implemented as much in the name of greed as in conservation.

J. HAWKWOOD
Harare, Zimbabwe

DOOMED TO A DEEP FREEZE?

I read with fascination "Snowball Earth," by Paul F. Hoffman and Daniel P. Schrag. After learning that Earth was rescued from the global ice age because volcanoes resupplied the atmosphere with carbon dioxide, which warmed the frozen planet, I began to speculate on the future. Eventually the radioactive fuel that drives such tectonic activity will be depleted, and Earth will become tectonically dead. Without mountain building, volcanism or seafloor spreading, no more CO_2 will be pumped into the atmosphere. Meanwhile the meteoric cycle will continue to scrub CO_2 from the atmosphere. Is it possible that the ultimate fate of life on Earth is an icy tomb?

MICHAEL A. DAVIES
via e-mail

Hoffman and Schrag reply:

Davies's scenario describes exactly what many scientists believe already happened on Mars. The planetary midget (only about one tenth of Earth's mass) cooled so fast that its CO_2-rich atmosphere was transformed to carbonate rock long ago, but Earth's fate will be more like the runaway greenhouse of Venus. The sun gets hotter all the time, and Earth adjusts by lowering levels of carbon dioxide through the weathering of silicate rocks. When all the CO_2 is used up, this thermostat will fail, and a Venus-like hellfire will ensue.

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Sandra Ourusoff
PUBLISHER
saourusoff@sciam.com

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415 MADISON AVENUE, NEW YORK, NY 10017
212-451-8523 fax 212-754-1138

Denise Anderman
ASSOCIATE PUBLISHER
danderman@sciam.com

Millicent Easley
SALES DEVELOPMENT MANAGER
easley@sciam.com

Peter M. Harsham
pharsham@sciam.com

Wanda R. Knox
wknox@sciam.com

Carl Redling
credling@sciam.com

MARKETING
Laura Salant *MARKETING DIRECTOR*
lsalant@sciam.com

Diane Schube *PROMOTION MANAGER*
dschube@sciam.com

Susan Spirakis *RESEARCH MANAGER*
sspirakis@sciam.com

Nancy Mongelli *PROMOTION DESIGN MANAGER*
nmongelli@sciam.com

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

CHICAGO
Rocha & Zoeller
MEDIA SALES
333 N. Michigan Ave., Suite 227
Chicago, IL 60601
312-782-8855 fax 312-782-8857
mrrocha@aol.com
kzoeller1@aol.com

LOS ANGELES
Lisa K. Carden
WEST COAST MANAGER
310-234-2699 fax 310-234-2670
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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
dfenn@canadads.com

EUROPE
Roy Edwards
INTERNATIONAL ADVERTISING DIRECTOR
Julie Swaysland
Chester House, 25 Ecclestone Place
London SW1W 9NF, England
+44 207 881-8434/35 fax +44 207 881-8503
redwards@sciam.com
jswaysland@sciam.com

FRANCE
Christine Paillet
AMECOM
115, rue St. Dominique
75007 Paris, France
+331 45 56 92 42 fax +331 45 56 93 20

GERMANY
Maren Scupin Günther
Am Wingertsberg 9
D-61348 Bad Homburg, Germany
+49-6172-66-5930 fax +49-6172-66-5931

MIDDLE EAST AND INDIA
PETER SMITH MEDIA & MARKETING
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JAPAN
NIKKEI INTERNATIONAL LTD.
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KOREA
BISCOM, INC.
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HUTTON MEDIA LIMITED
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Spektrum der Wissenschaft
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tel: +33-1-55-42-84-00

LE SCIENZE
Le Scienze
Piazza della Repubblica, 8
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

Early Robots,
Burst Bubbles and Old Mummies

MAY 1950

HYDROGEN BOMB AND DEMOCRACY— "On the hush-hush subject of the hydrogen bomb: here is a weapon about which the average citizen is so ill-informed that he thinks it can save the country from attack. Pumped full of hysteria by Red scares, aggravated by political mud-slinging, the average citizen is easily convinced that he can find some security and relief from all this in the hydrogen bomb. Here we have the outcome of what can happen in a democracy when decisions of far-reaching national significance are made without public scrutiny of pertinent information."

MECHANICAL LIFE— "Another branch of electromechanical evolution is represented by the little machines we have made in Bristol. Instead of the 10,000 million cells of our brains, Elmer and Elsie contain but two sense organs, one for light and the other for touch, and two motors. The number of components was deliberately restricted to two in order to discover what degree of complexity of behavior could be achieved with the smallest number of elements. Elmer and Elsie are in fact remarkably unpredictable. Crude though they are, they give an eerie impression of purposefulness, independence and spontaneity."

ANTIHISTAMINES AND SNAKE OIL— "Since the U.S. Food and Drug Administration approved the unrestricted sale of antihistamines last September they have become the most advertised and fastest-selling patent medicines in the U.S. The American public will spend an estimated $100 million this year for antihistamines to 'stop colds.' However, after carefully controlled studies the American Medical Association 'does not believe that the data prove that the antihistamines are useful for the prevention of the common cold.' Last month the Federal Trade Commission issued complaints against four manufacturers of antihistamines for 'false and misleading' advertising."

MAY 1900

TESTING TROLLEY RAILS— "We present an illustration of Lord Kelvin's rail-tester, which is used to determine whether there are any defects in the conductivity of the rails of an overhead trolley system. The track rails perform the important part of carrying the return current. In our illustration the contact bar of the tester is shown being applied at a joint in the rails in an endeavor to detect a faulty bond."

ELECTRIC TROLLEY RAILS: **the dutiful tester, 1900**

USEFUL TECHNOLOGY— "The telephone has proved very successful in the West in places where distant farmhouses are connected by wire, as it enables them to give each other timely warning of the approach of tramps. It is also useful in cases of fire and sickness."

RADIOACTIVE DECAY— "Emission of radiation possessing energy without any loss of weight in the radiation source would appear to be impossible from the view of conservation of energy. The measurements of M. Henri Becquerel upon the deviation of radium rays in an electric field, taken in conjunction with those of M. and Mme. Curie of the charges carried by those rays, show a way out of this difficulty, on account of the extreme minuteness of the quantities of energy. The energy radiated per square centimeter is of the order of one ten-millionth of a watt per second. Hence a loss of weight in the radium of about a milligram in a thousand million years would suffice to account for the observed effects."

MAY 1850

CALIFORNIA BUBBLE— "The news by the steamers from California is not at all favorable. The amount of gold dust falls short of the estimates indulged in, and the price current in San Francisco shows a rapid decline, which bears evidence that a revulsion has already commenced. It is entirely out of the nature of things, that such an intense excitement towards California could continue for a great length of time, without resulting in overwhelming reverses—that crisis has, to all appearances, arrived. Many will reap sorrow where prosperity was apparent. That San Francisco of last Fall has departed—that bustling, busy bee hive has ceased working."

GRAND GUIGNOL BY SUBSCRIPTION— "Mr. Gliddon, the Egyptian traveler, who is now lecturing in Boston and exhibiting his Panorama of the Nile, offers to open one of the mummies in his collection, if a suitable subscription can be raised. This mummy is the body of the daughter of a high priest of Thebes who lived more than 3,000 years ago, or about the time of Moses. Its market value is said to be about $1,500. A large number of our wealthy and influential citizens have already subscribed."

FROM SCIENTIFIC AMERICAN

SPORTS MEDICINE_DRUG TESTING

All Doped Up—and Going for the Gold

Miscues by the International Olympic Committee frustrate scientists developing tests for the performance-enhancing drugs erythropoietin and human growth hormone

This coming September, alongside the stirring spectacle of Olympic competition in Sydney, there will be another struggle so complex that the average viewer will probably have a hard time grasping the rules, let alone getting excited about it. Unfortunately, the loser will be fair competition.

The use of performance-enhancing drugs has long been one of the darkest aspects of sport, but the shadow has grown longer in recent years as evidence accrues that athletes are increasingly turning to two drugs relatively new on the doping scene: erythropoietin and human growth hormone. Like hundreds of other substances that are formally banned by the International Olympic Committee (IOC), these two are effective and fairly easy to get. Unlike the other agents, however, erythropoietin and human growth hormone are undetectable with the technology that sports officials currently use to catch drug cheats.

With sporadic funding from the IOC and other sources, researchers in half a dozen countries have been working feverishly over the past couple of years to come up with reliable tests for the two drugs. Unfortunately, although they have come tantalizingly close, the tests will probably not be ready in time for the Sydney games, several researchers say. More disturbing, scientists in three of the laboratories, in separate interviews, tell much the same story: they could have had the tests available for the games, but they were stymied by late decisions and a seeming lack of will at the highest levels of the IOC.

CYCLING IN THE BLOOD: **After seizures of the drug EPO during the 1998 Tour de France, police in Reims detained a member of the Dutch team TVM for tests and questioning. Seven teams were implicated; TVM withdrew, and another was expelled.**

FRANCIS DEMANGE *Gamma Liaison Network*

Without a reliable test, officials are at a loss even to say how widely abused the two drugs are. Scattered evidence suggests troubling pervasiveness, at least in some sports or among certain teams. "If this were a basketball game, we'd be behind about 98 to 2," remarks a former official of the U.S. Olympic Committee (USOC) who asked not to be identified.

Erythropoietin (EPO) is a hormone that occurs naturally in the body. Injected into the blood, it boosts the concentration of red cells and is favored by endurance athletes. It started catching on with competitors in the late 1980s, after a synthetic version was introduced to treat certain forms of kidney disease. Rigorous studies in Sweden and Australia have shown that EPO can improve an endurance athlete's performance by 7 to 10 percent.

In 1998 the Tour de France, the world's preeminent bicycle race, was thrown into disarray as investigators found caches of the drug in team vans, in car trunks and in the hotel rooms of competitors; a subsequent investigation concluded that use of the drug was endemic among cycling's elite. EPO is also blamed for the deaths of about 20 European riders since 1987. Although there is no hard proof that EPO caused the deaths, some doping experts believe the riders' blood thickened fatally after they took too much of the drug. Despite the 1998 scandal and the deaths, experts say EPO is still ubiquitous in cycling and is also widely used in cross-country skiing and long-distance running and swimming.

In contrast to EPO, human growth hormone (hGH) is a steroidlike agent that helps build muscle. Its use, however, may be just as widespread. In 1996 some athletes dubbed the Atlanta Olympics the "hGH Games." Around that time, a Latvian company was doing brisk business harvesting hGH from human cadavers and selling it for athletic use. In early 1998 a Chinese swimmer on her way to a competition in Perth was detained at the airport when she arrived with 13 vials of hGH packed in a thermos bottle. And just this past February 10, police in Oslo apprehended two Lithuanians harboring 3,000 ampoules of black-market hGH, according to Gunnar Hermansson, chief inspector of the drugs unit of Sweden's National Criminal Intelligence Service. The cache was enough to supply about 100 athletes for two months.

Reliable tests for EPO and hGH have eluded researchers for several reasons. The most imposing is that both substances are peptide hormones found naturally in the body. Thus, much of the research so far has focused on developing a so-called index test, in which an unusual combination of biological "markers" indicates drug use. The process would translate a variety of physiological parameters—for example, the concentration of red blood cells and the average age and size of the cells—into numerical values. If the combination of those values exceeded a certain number, officials could say with a high degree of certainty that the athlete had taken drugs.

The main project to develop the hGH test, at St. Thomas's Hospital in London, was suspended recently for lack of funding. According to Peter H. Sönksen, the project leader, his team had demonstrated by the end of 1998 a test that worked well on healthy Caucasian athletes. But he needed more funding to perform clinical trials to make sure the test worked with athletes of Asian and African descent, women taking birth-control pills, and athletes recovering from muscle injuries. "The estimated bill was $5 million," Sönksen says. "The IOC has decided not to invest further money to develop the test."

The IOC's decision is puzzling when considered in the context of the organization's other recent moves. Although the IOC apparently could not spare $5 million to finish the work on the hGH test, it did pledge early in 1999 to spend $25 million over two years to start a new antidrug bureaucracy, the World Anti-Doping Agency. Prince Alexandre de Merode of Belgium, chairman of the IOC's Medical Commission, which oversees antidrug activities, declined repeated invitations from Scientific American to explain the rationale behind the IOC's budgetary decisions.

DRUG TESTING begins in a locked room at the Olympic Analytical Laboratory at U.C.L.A., the largest such laboratory in the U.S. A window (*not visible*) lets other lab workers see the urine samples being prepared for a battery of tests by technician Daysi Lopez.

Sönksen says he gave the IOC ample advance notice that in order for his test to be ready in time for Sydney, he would have to undertake a sizable crash program of clinical trials. "Prince de Merode had warning from August 1998 that this was going to happen," he maintains.

The IOC still funds EPO research, having pledged $1.25 million to scientists working on a test. The leading team working on the EPO test is an international consortium based at the Australian Sports Drug Testing Laboratory in Pymble, a suburb of Sydney; a smaller effort is also under way at the drug-testing laboratory at the University of California at Los Angeles. An Olympic official in the U.S. who requested anonymity but is familiar with the work in both laboratories says it is very unlikely that the EPO test will be ready in time for Sydney. A researcher in the Australian laboratory confirms that the chances of having a test ready are slim, adding, "If we'd got the money when we asked for it, the chances would have been a lot better."

Associates of de Merode—himself a former competitive cyclist—say the prince is keenly aware of the toll EPO has taken on his favorite sport. Nevertheless, the IOC may have been reluctant to spend more on the development of index tests, some experts speculate, because such tests detect drug use by indirect means and are therefore more vulnerable to legal challenge by athletes who have been sanctioned for doping. "The ability to shoot holes in the prosecution process is greatly diminished when you have a direct test," explains David Joyner, chairman of the USOC's sports medicine committee and vice chairman of its antidoping committee.

The French IOC doping laboratory in Paris is developing a direct test for EPO. But it will not be ready for a few years, and researchers familiar with the test say it will be able to detect foreign EPO only if administered within three days of an injection. EPO is typically injected one to three times a week for a month before a competition. So the direct test probably will be useful primarily for precompetition spot checks of athletes.

Although a direct test would nicely complement an indirect one, most officials agree that an indirect test alone would be far better than none. And other than drug cheats, no one is happy that yet another Olympic Games will apparently unfold under the distorting influence of two pervasive and powerful performance enhancers. "There's no question we should have tests for growth hormone and EPO," says Don H. Catlin, director of the U.C.L.A. lab. "Sport has the money to support R&D commensurate with assuring clean games. If we want to preserve sport as we know it, we're going to have to pay for it." *—Glenn Zorpette*

REED HUTCHINSON *University of California at Los Angeles*

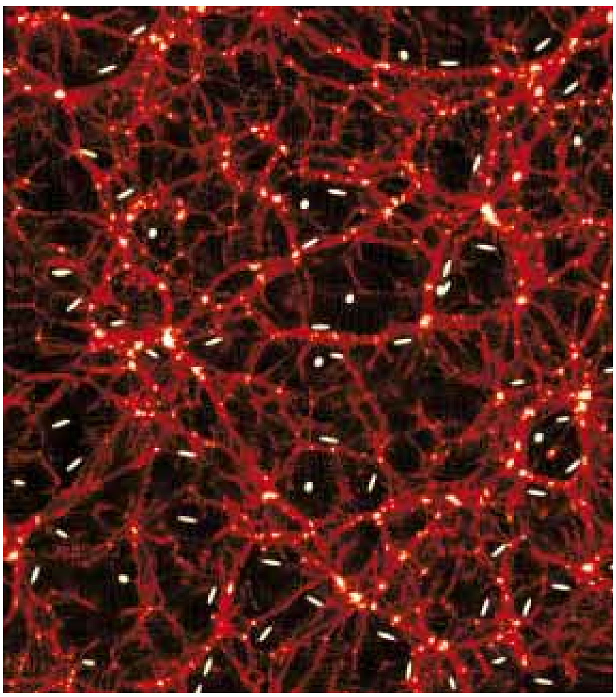
What's the Matter?

The prevailing theory for the universe's "missing mass" stumbles

Dark matter isn't terribly interesting stuff. Its identity may be a mystery, but whatever the material is, it must be deadly dull. It doesn't give off light or cast shadows or cohere into stars; it doesn't do much at all, except exert a brute gravitational pull evident only on cosmic scales. Or so scientists thought. Over the past six months they have wrestled with a radical idea: maybe dark matter leads a richer inner life than it seems.

For most of the seven decades since astronomers first suspected the existence of dark matter, it took all their ingenuity just to prove it. The familiar view of galaxies as big bundles of stars is now passé. Galaxies are really just giant balls, or "halos," of dark matter, with some stars sprinkled in. But what are the bodies unseen? One by one, the possibilities have faded away. Two leading searches—the MACHO survey, which ended in January after seven years, and the ongoing EROS survey—have found too few substellar objects, such as planets or brown dwarfs. Other observers recently glimpsed faint white dwarf stars in the halo, but there can't be too many of them, or else the by-products of their formation would litter interstellar space. In a paper published earlier this year Katherine Freese of the University of Michigan all but gave up the hunt: "Most of the dark matter in the galactic halo must be nonbaryonic."

In other words, it must consist of a whole new kind of elementary particle. Physicists have yet to spot it directly—new findings have called into question claims of so-called WIMPs, or weakly interacting massive particles—but astronomers think it must be "cold," that is, sluggish. Only slow-moving particles would have settled into galaxy-mass lumps. "Hot" particles such as neutrinos would have been much too flighty. Not long ago cold dark matter had its own lapses: theorists thought it would clump together too quickly. But the pieces fell into place two years ago, when astronomers discovered that cosmic expansion is accelerating; matter is unexpectedly dilute, which counterbalances the clumping tendency. Further evidence emerged this past February when several teams of astronomers unveiled the most extensive maps of matter yet. Galaxy clusters arrange themselves just as the cold dark-matter theory predicts they would.



COBWEB OF DARK MATTER can be inferred from how it distorts the images of some 170,000 galaxies (*ovals*).

JEAN-CHARLES CUILLANDRE *Canada-France-Hawaii Telescope Corporation* and STÉPHANE COLOMBI *Institut d'Astrophysique de Paris*

Ironically, just as astronomers corroborated the theory on large scales, they began to have doubts about it on smaller scales. Again, the difficulty is that cold dark matter would clump too readily. New high-resolution maps of certain types of galaxies suggest that their cores are less dense than predicted. On slightly larger scales the discrepancy manifests itself as a dearth of little galaxies.

"The canonical view of cold dark matter may be in trouble," says Paul J. Steinhardt of Princeton University. That conclusion is still controversial. But because the problems affect only fairly fine scales, astronomers hope they are a clue to the detailed properties of the dark matter.

Some, including Craig J. Hogan and Julianne J. Dalcanton of the University of Washington and Jesper Sommer-Larsen and Alexandre Dolgov of the University of Copenhagen, take the Goldilocks approach. Perhaps the matter is neither cold nor hot but lukewarm—just fleet-footed enough to shun small structures such as galaxy cores but not so zippy that it escapes galaxies altogether. Skeptics, however, argue that warm dark matter could fix either the galactic density profiles or the small-galaxy shortage, but not both.

In all the above hypotheses, the particles are linked to one another only by the two feeblest forces in nature, gravity and the weak nuclear force. But what if the particles were more sociable? Interacting among themselves, they could make up a sort of dilute gas able to resist gravity. In the inner reaches of a galaxy, they would jostle and space themselves apart. Farther out, the particles would hardly ever meet and so would behave just like ordinary cold dark matter.

Like warm dark matter, this idea came up briefly a decade ago. Steinhardt and his colleague David N. Spergel, now joined by other researchers, have thoroughly reworked it. If true, dark matter is more dynamic than is usually assumed. Small halos that flutter too close to big ones get evaporated. The matter is easier prey for central black holes, perhaps explaining how they grew so big. What worries skeptics, however, is that galactic cores would slowly lose heat and clump ever more tightly, in which case the theory ends up reproducing the failings of cold dark matter. Interacting dark matter might also make halos perfectly spherical, contrary to some observations.

Steinhardt and Spergel say everything works out if the particles have the same mass and interactivity as a neutron—an intriguing coincidence that, if substantiated, would be a huge breakthrough. The dark matter we perceive may be just a shadow on the wall, a mere hint of a vibrant world silently interleaved with our own.

—George Musser

AERODYNAMICS_INSECT

For the Bees

Glowing paint may highlight the forces that make insects fly

A honeybee with bright red wings buzzes past a young woman's ear. The bee's colorful airfoils would seem bizarre if the woman were sniffing an apple blossom, but rather she stands at a counter strewn with pipettes, a video camera, reference books, and a bee-filled yogurt container—in a chemistry laboratory at the University of Washington. There graduate student Christina M. McGraw paints bee wings in hopes of unraveling the mystery of insect flight.

Insects are often touted as the world's most versatile and maneuverable flying machines. Many of them can hover, loop—even turn in a distance as short as their own bodies. Yet they shouldn't be able to get off the ground, at least not according to the current reaches of solvable mathematics. The laws of quasi-steady-state aerodynamics easily explain the lift capabilities of rigid airplane wings. But insect wings flap and bend, and mapping the flow of air around moving boundaries takes an enormous leap in complexity.

Researchers have attacked this perplexing paradox in several ways, even by building a robotic fly. The problem is that most of these experiments and calculations treat insect wings as if they are stiff and do not describe the forces acting on them. Studying flexible bee wings, painted with a dye that responds to changes in air pressure, may provide the answers.

McGraw's advisers—James B. Callis, Martin Gouterman and their co-workers—perfected a paint in the early 1990s that can sense air pressure on airplane wings, a technology now exploited at aircraft-testing facilities around the world. The paint relies on a chemical dye known as a platinum porphyrin, which phosphoresces a brilliant red under ultraviolet light. Oxygen in the air quickly quenches the glow, a bit the way water thrown on a fire kills the flames. Spots on the wings that experience the highest air pressure phosphoresce the least, because more oxygen molecules are packed into denser air. By tracking the intensity of the glow, specialists can map out the forces acting on the wings.

Having discussed the mathematical subtleties of insect flight with Stephen Childress and Michael J. Shelley of New York University's Courant Institute, Washington physicist John S. Wettlaufer recently suggested to Callis that they use the same paint to study the flight dynamics of a hovering honeybee. The idea caught on, and bees became part of an ambitious $2.4-million collaborative project, funded by the National Science Foundation, to better understand how air and other fluids flow around moving boundaries—a phenomenon that applies to pumping heart valves as well as to flying insects.

HOVERING HONEYBEE proves much more difficult to describe mathematically than does a flying airplane, because insect airfoils flex as they flap.

STEPHEN DALTON *Photo Researchers, Inc.*

It didn't take long for a problem to surface: the patented airplane paint made bees' wings too heavy and stiff to fly. The Washington group tried mixing new paint, but hordes of bees died from the solvents. Dissolving the fluorescent dye in a fluid that contains honeycomb wax turned out to be the best solution. Using a pipette, McGraw now dabs each wing of an anesthetized bee with a tiny dot of paint, which spreads into a film only about two microns thick. When the bees wake up, almost all of them can fly around the room. "Going from mostly dead bees to mostly flying bees made it all seem a lot more possible," McGraw says.

The team has cleared the first hurdle, but although the bees can fly, Michael H. Dickinson of the University of California at Berkeley points out that even the thin film adds weight and stiffness that may change the way the bee flaps its wings. McGraw hopes to abate Dickinson's concern with the help of Washington zoologist Thomas L. Daniel and his graduate student Stacey Combes. They will glue a painted bee to the tip of a cantilevered syringe needle and reflect a laser beam off the base to measure the lift and thrust created when the bee flaps its wings. If these force measurements match those of unpainted bees, the team will be sure it's on target. "As skeptical as I am, I sure hope it works," Dickinson says.

Recent advances in computational fluid dynamics and computer power will help the team achieve its ultimate goal. Childress, Shelley and their colleagues recently simulated the forces around a two-dimensional insect wing on a computer and have shown that vortices of swirling air produced in an upstroke actually add lift during the downstroke. If the Washington experiment works, it should be able to show whether the same thing happens in real life.

Still, creating a pressure map of a bee wing in flight will require the detection of changing forces that, Gouterman cautions, may be too subtle. A bee's complete wing-beat cycle takes place in a mere five milliseconds, and even that rapid flapping generates only a hint of lift. But Gouterman says he also reacted with skepticism back when Callis first dreamed of developing pressure-sensitive paint to test airplanes. Now both researchers are enjoying royalties from their patents. "When Jim Callis gets ideas," Gouterman remarks, "he often gets them to work."

—Sarah Simpson

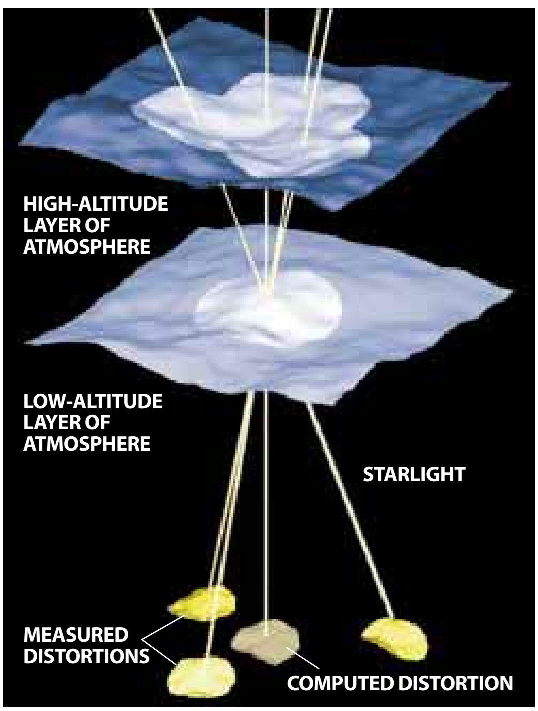
Three-Star Performance

Tomography from the ground could outdo the Hubble and its successor

The twinkling of the stars is fine for nursery rhymes and poets but much less charming for astronomers. Atmospheric turbulence causes the twinkling and more generally distorts images; left uncorrected, a state-of-the-art 10-meter telescope would achieve only the same optical resolution as an amateur's backyard scope (albeit with much greater light-gathering capacity). The 2.4-meter Hubble Space Telescope, riding expensively in orbit up above the turbulence, embodies one spectacular solution. Over the past decade, astronomers have taken great strides in applying another solution, called adaptive optics: light from a bright star is used to detect the atmospheric distortions, and a continually adjusted deformable mirror corrects for them. Though increasingly popular, the technique is so far limited to the 1 percent or less of the sky that lies close enough to a sufficiently bright star.

Astronomers have now demonstrated the advantages of a more sophisticated technique called multiconjugate adaptive optics, which uses light from several stars or lasers to produce, in effect, a three-dimensional map of the turbulence. With this method, optical corrections can be made across larger patches of sky. Multiconjugate techniques would improve the current generation of 8- and 10-meter aperture telescopes and "will be absolutely essential for the ultralarge, 100-meter telescopes now being discussed," says Robert Q. Fugate, an adaptive optics expert working at the Air Force Research Laboratory at Kirtland Air Force Base near Albuquerque.

In standard adaptive optics using a single guide star, the quality of the optical correction rapidly decreases the farther the target is from the guide star. This occurs because light from a star at the edge of the field of view crosses different patches of the turbulent layers. The effect becomes more pronounced with a larger-aperture telescope. As well as simply degrading the resolution, the resulting variation of resolution across an image makes data harder to interpret. To achieve more uniform correction of images, one therefore needs a three-dimensional map of turbulence in the field of view. To produce such a map, one must analyze the light from more than one guide star, much as medical tomography of a patient uses x-rays sent along different lines of sight.



WARP FACTOR 3: Measured distortions from three stars enable those from another to be computed.

ROBERTO RAGAZZONI *Astronomical Observatory of Padua*

An Italian group carried out such tomography for a small Y-shaped constellation of four stars using a 3.6-meter telescope. The group, led by Roberto Ragazzoni of the Astronomical Observatory of Padua observed the light from the outer three stars and stitched together the data to deduce accurately how light from the central star was deformed.

The experiment did not include any actual image correction, but in principle the tomographic data could drive two deformable mirrors, effectively correcting for turbulence at two distinct altitudes. The group's results demonstrate that such a system would outperform a single-mirror system. Ragazzoni predicts that on future extremely large telescopes the technique could enable full sky coverage without the need for laser guide stars—spots of light created in a sparse natural layer of sodium atoms that lies about 90 kilometers up. Brent Ellerbroek of the Gemini Observatory in Hawaii, however, cautions that how multiconjugate systems will scale up to 100-meter telescopes "has not yet been shown either theoretically or experimentally."

Systems using a single laser guide star were developed for military imaging and laser weapons programs and are now one of the most active areas of civilian adaptive-optics research. Laser guide stars solve the sky-coverage problem because the artificial guide star can be placed anywhere in the sky (although a faint natural guide star is still needed in the vicinity). Use of a single laser guide star still suffers, however, from sharply deteriorating resolution across the field of view. In addition, developing a suitable laser-projection system with a sufficiently bright and well-focused beam at a 90-kilometer range has proved to be a major technological challenge. A few preliminary systems are now on-line, including the ALFA (Adaptive optics with a Laser For Astronomy) system on a 3.5-meter telescope at Calar Alto in southern Spain, which has surpassed the Hubble in resolution for infrared observations.

The Gemini adaptive-optics group is proposing to install a multiconjugate system using four or five laser guide stars on its 8-meter Gemini South telescope, now being constructed at Cerro Pachón in the Chilean Andes. Three deformable mirrors would correct for turbulence at different altitudes to reap the tomographic benefits. The Gemini system would be operational in 2004 and would not just surpass Hubble. For some tasks, it should equal Hubble's successor, the next-generation space telescope (NGST), which will have an 8-meter class mirror and is not scheduled to be launched until late 2008. Ellerbroek predicts that the Gemini system could "address a significant fraction of the NGST science programs" four years earlier than that. And in the "NGST era," Gemini would remain a powerful complement to it, much as large ground-based telescopes currently complement the Hubble. *—Graham P. Collins*

PALEONTOLOGY_DINOSAURS

A New Rex

The biggest meat eater of them all bolsters the theory of pack hunting

PLAZA HUINCUL, ARGENTINA—Whereas many dinosaur hunters rack up frequent-flier miles crisscrossing the globe, Rodolfo Coría just needs his trusty white pickup truck to roam this fossil-rich corner of northern Patagonia. As director of the Carmen Funes Municipal Museum in Plaza Huincul, Argentina, Coría and his colleagues have found at least 10 new dinosaur species in the past decade within a two-hour drive of the museum, a squat cinder-block building on the outskirts of a former oil boomtown. So it was not too surprising when Coría and his co-worker Philip Currie, director of the Royal Tyrrell Museum of Paleontology in Alberta, Canada, announced on March 10 that they had found the remains of six individuals of a new theropod, or meat-eating dinosaur, that could be the biggest meat eater to have ever walked the earth. "This is a good place for dinosaurs," Coría said during a day of excavation at the dig site in late February.

That may be an understatement. In 1993 Coría excavated and described the current record holder for largest predator, the 45-foot-long *Giganotosaurus carolinii,* which he found, after a tip from an amateur fossil hunter, about 30 miles from Plaza Huincul. And in 1997 he found several thousand fossilized eggs from a giant sauropod, or plant-eating dinosaur, just 120 miles north. The find included the first-known fossilized dinosaur embryos, as bits of fossilized dino-skin. In 1996 a colleague discovered Megaraptor, a 30-foot-long hunter with a 13-inch slashing claw, in a mudstone quarry within sight of the museum.

The latest find includes one large adult, two smaller ones, two juveniles and one quarter-size "baby" dinosaur. Because they were found all together with no indications of volcanic eruptions or attack by other dinosaurs, the paleontologists theorize that the group—perhaps a family—may have perished in a flood.

The new animal, whose name is being kept secret until publication in a journal later this year, resembles in many ways the other large theropods, *Tyrannosaurus rex* and *Giganotosaurus,* with powerfully built legs, a thick tail and small forelimbs. But it was most likely 10 percent larger than *Giganotosaurus,* which lived 95 million years ago. With similar body shapes, the two probably shared a common ancestor. But the new dinosaur's features were more primitive: a narrower and slightly shorter skull, as well as differences in the sinus openings. Its serrated teeth could slice its prey with surgical precision, and researchers say the animal could devour a human in a single mouthful.

REMAINS OF THE DAY: Fossilized bones of a giant meat eater are prepared for transport.

JOEY IVANSCO *Atlanta Journal-Constitution*

"We know more about the development of this dinosaur because we have found adults and juveniles," Coría said while preparing a bone of the new theropod with the help of his 13-year-old daughter, Ludmilla. "This doesn't happen very much in paleontology."

After covering the bones with wet toilet paper, burlap and then a plaster cast, Coría hauled them up to his pickup. They are off to the Plaza Huincul museum, about a half-hour drive away. There they will join the bones of another brand-new theropod that he found last year, a 30-foot-long animal that he hasn't fully described yet.

During the late Cretaceous, this arid section of Argentina was a well-watered zone of conifer forests and open grasslands. The idea of a pack of killer theropods roaming this region some 85 million years ago bolsters Currie's theory that carnivores were more social than previously believed. Pack hunting would have made sense, especially when trying to bring down the giant plant eater of the day: the 100-foot-long, 100-ton *Argentinosaurus* (discovered nearby). Faster juveniles would have separated herds of these beasts and driven younger ones toward the larger adult carnivores, according to this theory.

Although fossils of North America's big predator, *T. rex,* have almost always been discovered by themselves, a find three years ago by Currie points to the possibility of pack behavior by the smaller meat eater, *Albertosaurus:* a group of 10 was found along the Red Deer River in Alberta. He believes they hunted as a pack but hasn't yet published his research.

Thomas Holtz, a vertebrate paleontologist at the University of Maryland, says the new fossils in Argentina are significant because they represent the best evidence for family life in large theropods, especially if there is no other explanation for finding them together. But he notes that researchers should be cautious about inferring too much from skeletons. "Look at lions and tigers," Holtz points out. "They are anatomically similar, and few could tell them apart from just their skeletons. But their social behaviors are completely different. Tigers only hunt as solitary individuals, while lions are the ultimate in pack hunting." Whether lions lose that distinction to dinosaurs remains to be seen. *—Eric Niiler*

ERIC NIILER is a freelance science writer based in San Diego.

Physician, Heal Thyself

Disagreement swirls around a plan to prevent errors in hospitals

When the topic of medical errors comes up, people usually think of the most outrageous mistakes: the Florida doctor, for example, who amputated the wrong leg of his diabetic patient or the Colorado boy who died during ear surgery because his anesthesiologist allegedly fell asleep. Though much publicized, these egregious errors are relatively rare. Far more common are mental lapses or simple slip-ups that sometimes lead to disaster. For instance, a harried doctor misdiagnoses a patient because he cannot spend more than five minutes examining her. Or a pharmacist dispenses the wrong drug because he misreads the doctor's handwriting on the prescription.

Last fall the National Academy of Sciences's Institute of Medicine released a report entitled "To Err Is Human," which claimed that between 44,000 and 98,000 Americans die every year as a result of medical errors. Even the lower estimate would make errors the eighth leading cause of death, striking down more people than motor vehicle accidents or breast cancer. The report outlined a series of recommendations aimed at reducing medical errors by 50 percent over the next five years. It advocated an approach similar to that used by the aviation industry, with the focus on collecting information on errors and using this knowledge to devise safer systems and procedures. President Bill Clinton has already endorsed the report, and Congress may act on several of its recommendations this year.

The leaders of the medical community, however, are deeply suspicious. Some say the report draws sweeping conclusions from scanty evidence. Only two large studies of medical errors have been conducted: an examination of 30,000 randomly selected patient records from hospitals in the state of New York in 1984 (called the Harvard Medical Practice Study) and a review of 15,000 records from Colorado and Utah hospitals in 1992. The researchers measured the frequency of "adverse events"—patient injuries caused by medical care—then judged whether the events were preventable. "It's excellent research, but it's thin," says Troyen A. Brennan, a Harvard Medical School professor involved in both studies. "For example, we saw a tremendous variation of rates from hospital to hospital, but we don't know how they change from year to year. A lot of basic information is not available." The estimates of deaths caused by errors are particularly shaky, Brennan notes, because it is often impossible to determine whether a patient died from an error or from his or her disease.

Twenty states currently require health care facilities to report medical mistakes, but their guidelines are inconsistent—each state has its own definition of error. More important, the state health departments do not have the resources to analyze the data adequately so that they can identify the most common mistakes. The Institute of Medicine's report recommended the creation of a nationwide reporting system and a new federal agency, the Center for Patient Safety, to coordinate the collection and analysis of the data. The agency's initial budget would be about $30 million. "It's a drop in the bucket," says William C. Richardson, president of the W. K. Kellogg Foundation and chairman of the committee that wrote the report. "We're spending much more to prevent aviation accidents, and they kill far fewer people." (If the airline industry's fatality rate was as high as the estimated death rate from medical errors, five major crashes would take place every day.)

The proposed reporting system, though, has drawn fire from the American Medical Association (AMA) and the American Hospital Association. Under the plan, state health departments would require hospitals to report all errors that result in serious injury or death; less harmful errors would be reported on a voluntary basis. To ensure that hospitals are held accountable for their worst mistakes, some of the information on serious errors would be made public. The medical organizations argue that this provision would give doctors and hospital administrators a strong incentive to hide their mistakes. "Our fear is that people will find ways to avoid reporting," says Nancy W. Dickey, past president of the AMA. In all likelihood, state health departments would have to send teams of auditors to each hospital to encourage compliance.

Seeking an alternative to this punitive approach, the medical organizations are trying to tackle the problem themselves. In 1997 the AMA established the National Patient Safety Foundation, which has funded research on medical errors and is now beginning to disseminate the results. Much of their work is focused on preventing errors in prescribing and administering medications. Some hospitals have already set up computerized drug-ordering systems that require doctors to spell out drug names and dosages instead of scrawling them in illegible handwriting.

But the health care industry may need more prodding from the government. Over the past 20 years the advent of managed care has intensified the financial pressures on doc-

MISTAKEN AMPUTATION in 1995 left Willie King, a Florida retiree, without the lower parts of his legs.

PETER COSGROVE *AP Photo*

tors and hospitals. Some new studies suggest that cost-cutting measures, such as reductions in hospital staffs, can increase the potential for error. "Doctors need time to make a diagnosis," says Kenneth M. Ludmerer of the Washington University School of Medicine. "A physician can miss all sorts of things if he has to treat a patient in just a few minutes."

Perhaps the best strategy for combating medical errors is to follow the example of the U.S. Veterans Health Administration, which is widely praised for the safety efforts at its 173 hospitals. When a serious error is reported at a V.A. hospital, a panel of staff members investigates the event and recommends changes. Some solutions are high-tech: to prevent patients from getting the wrong drugs, the V.A. is equipping its nurses with handheld scanners that can match the bar codes on drug vials with those on patient-identification bracelets. The head of the V.A.'s safety program is James P. Bagian, a former space shuttle astronaut who served on the team that investigated the *Challenger* explosion. Says Bagian: "Just telling doctors and nurses to be more careful won't do very much. We need to change the systems that allow errors to happen." *—Mark Alpert*

ECONOMICS_LABOR

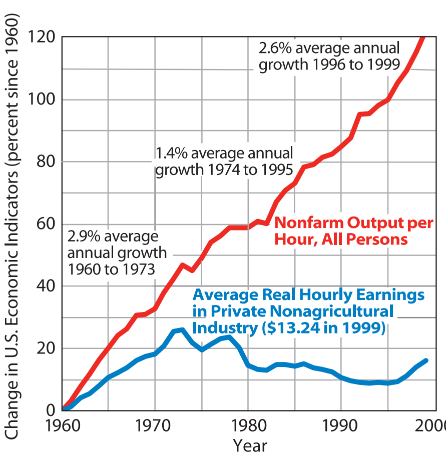
Productivity

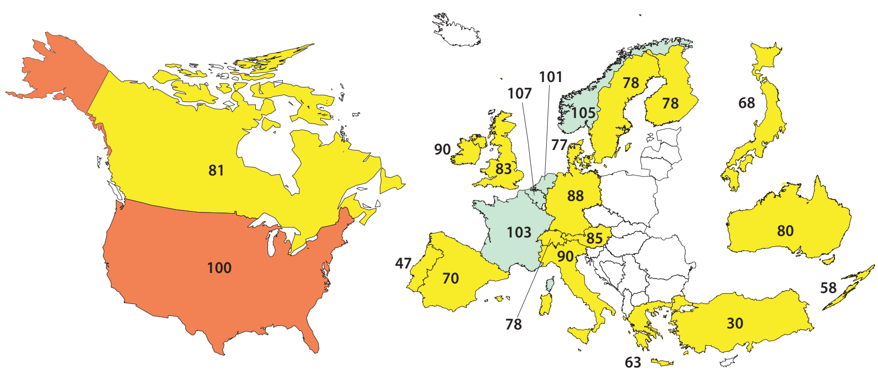
For the first time since the 1960s, U.S. productivity has been growing at an annual rate above 2.5 percent. As numbers go, this may not seem spectacular, but it has enabled the economy to sustain a very low level of unemployment—less than 5 percent in each of the past three years—while holding retail price inflation to about 2 percent a year. The late stages of most business cycles put irresistible pressure on employers to raise wages, which ordinarily leads to increased prices and in turn acts to slow or stop the expansion. But in the present circumstances, employers can raise wages without upping prices because of increased productivity.

According to the President's Council of Economic Advisers, about half of the increase in productivity since 1995 is explained by increased capital equipment—particularly computers and software—plus increased productivity in the computer-manufacturing industry. The remaining half of the productivity increase may reflect new efficiencies from Internet use by business and the normally greater efficiency of employees during periods of high demand.

The better educated benefited the most from the rise in productivity. Average hourly earnings in private, nonagricultural business increased in real terms by about 16 percent during the past 40 years, but professionals did better: physicians, for example, enjoyed an increase in real earnings of 33 percent in the same period. One way of looking at the benefits of rising productivity is to compare various family income groups. The top 5 percent of families had an increase in income of 129 percent in real terms from 1960 to 1998, while the middle fifth had an increase of 54 percent and the bottom fifth only 38 percent. Family income went up not only because productivity was greater for other reasons, such as the increasing number of wives taking jobs outside the home. The average real income of working Americans, as the chart shows, increased beginning in 1995—undoubtedly made possible by the spurt in productivity over the same period.

In 1950 northwestern Europe, as measured by gross domestic product (GDP) per hour worked, was half as efficient as the U.S., but now it is about 90 percent as efficient, and a few countries, including France, were marginally ahead as of 1997. The U.S., however, is far ahead of France—and every other country—in terms of GDP per capita, in part because Americans put in longer hours and because proportionately more are economically active. In France and Germany, for example, only 48 percent of the civilian working-age population actually worked in 1997, as compared with 64 percent in the U.S. Lower labor-force participation and high unemployment rates, as exist in much of Europe, suggest that the least skilled are excluded and so do not drag down productivity. By comparison, the U.S. economy has created millions of jobs for less skilled and presumably less productive workers. Few, however, would disparage low unemployment for this or any other reason. *—Rodger Doyle (rdoyle2@aol.com)*





Gross Domestic Product per Hour Worked in 1997 (Index: U.S.=100)

Less than U.S. | U.S. | More than U.S. | No data

SOURCES: ***CHART:*** *U.S. Bureau of Labor Statistics. Average hourly earnings are deflated by the consumer price index to compute real hourly earnings. Adjustment by another widely used index, the GDP deflator, would have resulted in a trend line somewhat closer to that of nonfarm output per hour.*

MAP: *"International Comparisons of Labor Productivity and Per Capita Income." Bart van Ark and Robert H. McGuckin in* Monthly Labor Review, *1999, pages 34–41; July 1999. Available data are shown for all members of the Organization for Economic Cooperation and Development.*

RODGER DOYLE

CHILD DEVELOPMENT

Formula for Intelligence?

Researchers may have found a food that makes you smarter—if you're a baby. According to the March *Developmental Medicine and Child Neurology,* infants fed baby formula supplemented with two fatty acids found in breast milk, docosahexaenoic acid and arachidonic acid, performed better on tests of mental development than did a control group of infants who received plain formula. The test used is similar to an IQ test—100 points is average. The mean result for infants on enriched formula was 105; babies fed plain formula scored 98. The spread of scores was notable as well: 26 percent of infants on the fortified diet scored over 115, compared with only 5 percent of those on plain formula. And 10 percent of the control group scored below 85; none in the enriched group showed this delayed development. The study, which looked at 56 babies fed formula in their first 17 weeks, points out that the role of breast feeding versus formula feeding in cognitive development remains controversial. See www.cup.cam.ac.uk/journals/dmc/birch.pdf —*Sasha Nemecek*

MATHEMATICS

Jam Session


Random sphere packing

THOMAS A. KELLY AND GAIL MOONEY *Corbis*

Cramming as many items as possible into a given space is a real challenge for business—and mathematicians. The optimal arrangement for oranges and other round fruit is the so-called face-centered cubic array, in which the objects are stacked in layers greengrocer-style. This arrangement fills 74 percent of the available space, the densest possible. Conventional scientific wisdom held that randomly dumping spheres into a container results in a looser configuration, taking up about 64 percent of the space. But in the March 6 *Physical Review Letters,* Princeton University's Sal Torquato and his colleagues explain that spheres occupy 64 percent of a volume only when the objects fill the space in the most disordered way possible. Their computer simulations show that the density of the "random packed state" actually varies from 64 to 74 percent, and because it is not fixed, the state is not a precise concept. Torquato proposes a new packing standard, the "maximally random jammed state": spheres packed so tightly that none can budge and are most inefficiently filling the space. —*Philip Yam*

ENGINEERING

From Power Lines to Pantyhose

To celebrate a remarkable era of technological achievement, the National Academy of Engineering revealed in February a list of the 20 marvels of engineering that have had the greatest influence on quality of life in the 20th century. Compiled by leading engineers from 30 professional engineering societies, the list covered a wide range of endeavors, from the electrification of the world, which was voted number one, to the development of high-performance materials such as synthetic fibers. In between were advancements that have revolutionized the way people live (safe water supply and treatment and health technologies), work (computers and telephones), play (radio and television) and travel (cars and airplanes).

Surprisingly, today's sophisticated information superhighway, the Internet, ranked behind the weather-beaten, well-worn roads of the nation. And astronaut Neil Armstrong, who was the one to announce the list at a luncheon, was probably a bit shocked to find that spacecraft did not make it into the top 10. For historical details of each, see www.greatachievements.org —*Diane Martindale*


KEVIN FLEMING *Corbis*

No. 11: 44,000 miles of U.S. interstate highway

The Top 20 Engineering Marvels

1. Electrification
2. Automobile

3. Airplane
4. Water Supply and Distribution
5. Electronics
6. Radio and Television
7. Agricultural Mechanization
8. Computers

9. Telephone
10. Air Conditioning and Refrigeration
11. Highways
12. Spacecraft

13. Internet
14. Imaging
15. Household Appliances
16. Health Technologies

17. Petroleum and Gas Technologies
18. Laser and Fiber Optics
19. Nuclear Technologies

20. High-Performance Materials

JARED SCHNEIDMAN DESIGN

ANTHROPOLOGY

Axes to Grind

In the 1940s Harvard University anthropologist Hallam L. Movius, Jr., observed that archaic humans living in western Eurasia and Africa between 1.6 million and 200,000 years ago crafted sophisticated stone tools such as hand axes and cleavers but that people in East Asia seemed stuck in a technological rut. Their much simpler tool remains implied that they were culturally, and perhaps biologically, isolated.

Now a windfall of carefully chipped cobbles from southern China's Bose Basin reveals that 800,000 years ago, East Asian hominids were fashioning tools as complex as those of their Eurasian and African counterparts. The stratigraphically restricted nature of the discovery suggests that their access to previously unavailable raw materials—cobblestones newly exposed by widespread forest fires—sparked the manufacture of the advanced implements. The findings appear in the March 3 *Science*. —*Kate Wong*

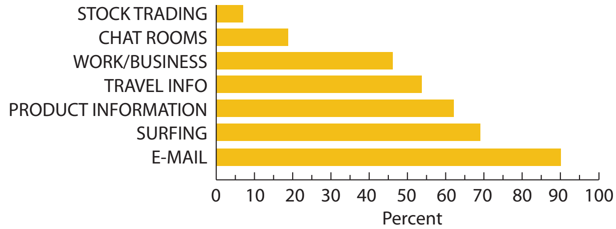
Oldest Asian axes

RICHARD POTTS AND HUANG WEIWEN

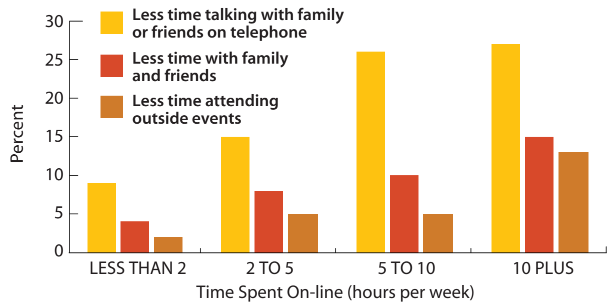
DATA POINTS

Yeah, You've Got Mail

What Users Do on the Internet



Social Isolation: Internet Users Reporting...



EDWARD BELL

- **Percent of households consisting of one person in 1969: 16.7**
- **Percent in 1998: 25.7**

SOURCES: Stanford Institute for the Quantitative Study of Society; U.S. Census Bureau.

PROSTHETICS

Lending a Helping Leg

After 40 years of playing around, Barbie, an American icon for millions of girls, has found a new job: she is lending a helping leg to finger amputees. Jane L. Bahor, an anaplastologist (someone who specializes in making realistic replacement body parts) at Duke University Medical Center, has discovered that a Barbie doll's flexible knee joint can be implanted into prosthetic fingers, making them much more functional and lifelike.

The ratchet leg joint acts like a bone, creating a scaffold around which foam is attached and sculpted into a natural-looking finger, Bahor explains. The joint makes a perfect substitute finger because it bends and holds a position—something previous prostheses, made with wire, could not do.

Bahor and former engineering student Jennifer Jordan, who needed a finger prosthesis herself, came up with the idea during a brainstorming session four years ago. At first, Bahor literally performed mini plastic surgeries—an incision down the length of Barbie's leg—to remove the tan plastic joint inside. Once Barbie's maker, Mattel, learned of the anaplastologist's experiments, it sent her hundreds of the lightweight body part.

Patients fitted with her prosthesis can quickly bend their fingers by pressing them against a hard surface or by using their other hand. Although the fingers lack feeling, the increased mobility provided by the Barbie joint allows wearers to hold a cup, to pick up a piece of paper and even, in some cases, to write again, Bahor says (although kung-fu grip may be out of the question).

The only drawback is "the noise they make; it sounds like cracking knuckles," Bahor points out. She now attempts to reduce the click noise by working the joints in a bit before using them in the prosthesis, allowing those sporting a Barbie knuckle to do so a little more quietly. —*D.M.*

PHOTOGRAPHS BY CHRIS HILDRETH *Duke University Medical Center*

BARBIE SCAVENGER Jane L. Bahor fills the space around the joint by injecting foam into the silicon finger mold. Removing the knee joints from the doll requires mini plastic surgery (*right*).

PROFILE_GÜNTER BLOBEL

The Biologist and the Cathedral

Who wants to give away a million dollars? This 1999 Nobelist does—to rebuild one of Germany's Baroque landmarks

NEW YORK CITY—One of the most formative experiences in Günter Blobel's life was encountering the *Frauenkirche*—the Church of Our Lady—as a child in Dresden, Germany. It was February 9, 1945, and eight-year-old Blobel and his family were fleeing to find safe haven from the Allied bombs that were falling over Nazi Germany. As they passed through Dresden, Blobel was particularly dazzled by the beauty of the Protestant church's dome—the "stone bell" that had towered 90 meters over the skyline of the city for 200 years.

But he did not have long to enjoy his view of the *Frauenkirche*. Four days later Blobel and his family watched with horror from the nearby hills as ton after ton of Allied ordnance rained on Dresden, igniting a firestorm that laid waste the city's Baroque-era treasures and took tens of thousands of lives. The glow from the conflagration illuminated the countryside for miles: "You could read a newspaper by it," Blobel recalls. For two days the *Frauenkirche* burned, until finally the exquisite structure groaned, and its stones collapsed into a pile of charred rubble.

"IT WASN'T A SUNDAY AFTERNOON DISCOVERY": 1999 Nobel laureate Günter Blobel's work on how proteins cross membranes goes back to 1971.

STUART RAMSON *AP Photo*

Blobel, his parents, and his seven brothers and sisters escaped the attack on Dresden, although one of his sisters died in a train bombing a few months later at the age of 19. Her death and the vision of the elaborate *Frauenkirche* and its destruction have stayed with him throughout his life.

So last October, when Blobel won the Nobel Prize in Physiology or Medicine for his work on how proteins wend their way through the labyrinths of membranes within cells, his thoughts turned to how the $960,000 award that accompanies the prize could benefit the ongoing effort to rebuild the *Frauenkirche*. Blobel donated the entire amount of his award money to the Friends of Dresden, an organization he founded in 1995 to help the international push to reconstruct the church.

As a biologist, Blobel has devoted his career to studying structures. The individual cells that make up humans, other animals and plants are tiny cathedrals in themselves, with arches and buttresses of membrane that give them substance and that make up the specialized structures called organelles that carry out the various functions of life.

Blobel did not start out wanting to be a scientist; he trained at the University of Tübingen to become a doctor. Indeed, medicine is a big part of Blobel's family history. His father was a large-animal veterinarian who cared for livestock on baronial estates near the family home in Silesia, a former province of Germany that is now part of Poland. Two of his brothers went on to become veterinarians, and another is a physician.

Blobel had just finished his medical internship at various German hospitals in 1962 when he decided to shift gears and go into research instead. "When I was doing my internship, I realized that lots of diseases were treated symptomatically," Blobel says. "I wanted to treat the cause."

Once he made the switch to research, Blobel sought to come to the U.S. for training, even though, he recounts, "I was very attached to Europe." But his first efforts were unsuccessful: his application to become a Fulbright scholar was rejected. Then one of his brothers, who was by then a professor of veterinary medicine at the University of Wisconsin–Madison, helped him get into the Ph.D. program in oncology there. "I instantly liked it," Blobel remembers. "There was nice social life." Still, he thought that his stint in the U.S. was temporary and that he'd eventually end up back in Europe. "I'd made up my mind I wouldn't stay forever."

But Blobel has been in the U.S. ever since and is now an American citizen. After obtaining his degree, he took a postdoctoral fellowship in the laboratory of George Palade at the Rockefeller Universi-

DOME OF THE *FRAUENKIRCHE* dominates the Dresden skyline in a 1747 painting (*right*). But after the Allied firebombing of February 13 and 14, 1945, only ruins remain, as shown in the postwar photograph below. An international rebuilding effort aims to restore the Protestant church to its former glory.

THE HERMITAGE, ST. PETERSBURG/BRIDGEMAN ART LIBRARY (*painting*); HANS MADEJ *Bilderberg* (*photograph*)

ty, who himself received the Nobel Prize in 1974 for his work on how cells synthesize proteins. And at Rockefeller, Blobel and another young researcher, David Sabatini, began to develop the ideas that would earn Blobel his Nobel.

Cells synthesize proteins on particles called ribosomes, which stick to the outside of the endoplasmic reticulum (ER), a network of membranes that laces through a cell. Ribsomes are the assembly lines where molecules of messenger RNA, which contain genetic information copied from DNA in the nucleus, are used as the blueprints for stringing together amino acids to make proteins. Studies by Palade and others had shown that some newly formed proteins somehow traverse the ER membrane, enter the ER interior and end up being secreted by the cell in tiny bubbles of membrane called vesicles.

Blobel and Sabatini wanted to know how such finely orchestrated trafficking of proteins could occur. After all, proteins are generally water-loving molecules, yet they manage to traverse the oily barriers of intracellular membranes to get from one part of a cell to another. The biologists proposed in 1971 that each nascent protein must have a signal at one end that serves as a tag for addressing it to its correct place.

Although Sabatini went on to other studies, Blobel continued to pursue what became known as the "signal hypothesis." As he rose through the ranks to become a full professor at Rockefeller in the 1970s, Blobel identified the cellular address tag, which he called the signal peptide. By the early 1990s he and colleagues working in his laboratory had identified the tunnellike pore that proteins use to traverse membranes, which explains how watery proteins can move through oily barriers. They had also put together the entire biochemical sequence through which secreted proteins enter the ER and had figured out how proteins whose jobs require them to remain stuck in a membrane get that way.

Blobel's findings have important implications for understanding and treating a variety of diseases, including Alzheimer's, the early development of kidney stones and cystic fibrosis. In the latter disease, for example, the protein that regulates the level of a type of salt within cells never reaches the cell surface. The result is the buildup of sticky mucus in the lungs and other organs, which can predispose a patient to potentially deadly infections.

Blobel—a tall, garrulous man with thick white hair who retains touches of his German accent—claims he was surprised when he received the call from Sweden notifying him he'd won the Nobel, although his name had been bandied about as a candidate among biomedical scientists for years. His decision to donate the prize money for reconstructing the *Frauenkirche* was made "without even thinking," Blobel says. "It was very clear I would do it."

It's not every day that someone gives away nearly $1 million that has just fallen into his lap. Most Nobel Prize–winning scientists have toiled for years for moderate salaries at academic institutions and justly view the windfall as delayed compensation. Some pour the money into their research, some buy houses, others spend at least part of it on something frivolous, such as the 8,000-square-foot croquet lawn built by Richard J. Roberts of New England Biolabs, who won the Physiology or Medicine Nobel in 1993.

But Rockefeller is known for its generosity to its faculty, and Blobel is also an investigator for the Howard Hughes Medical Institute, which is one of the largest funders of biomedical research in the U.S. other than the National Institutes of Health. And Blobel and his wife, Laura Maioglio—who owns the acclaimed Barbetta restaurant in midtown Manhattan—never had children, "which I regret," he says. So although they could have bought a weekend house to complement their Park Avenue apartment, they decided the money should go to the *Frauenkirche*.

Blobel's contribution brings the budget of the Friends of Dresden to roughly $2 million—one fifth of the amount needed to rebuild what he calls "an American wing" of the church. The entire effort, due for completion in 2004, is estimated to cost approximately $200 million, which is being raised by other groups and corporations around the world. "I hope my gift of the Nobel Prize money will stimulate people to give more," Blobel says.

—Carol Ezzell

GÜNTER BLOBEL: FAST FACTS

- **Born in Silesia—a former German province now part of Poland—in 1936**
- **Has a two-foot-high model of the *Frauenkirche* in his office, which also serves as headquarters for the Friends of Dresden, Inc.**
- **Was the 20th Nobel laureate from the Rockefeller University**
- **Wife's truffle-sniffing dog, Diana, once took part in a truffle-finding event onstage at Carnegie Hall in New York City. Dog hid under wife's skirt**

Wired for Speed

As chips shrink, researchers look to optical and radio-frequency interconnects

Every few years scientists and manufacturers from all over the globe draw up what is now called the International Technology Roadmap for Semiconductors, an assessment of semiconductor technology requirements and research goals over the next 15 years. Ironically, one of the biggest challenges the industry faces is traffic congestion on and between the chips themselves.

Thanks to ever shrinking transistors on integrated circuits (ICs), computers have become quicker and more powerful. But as faster and smaller transistors are packed onto a microchip, the layers of wires that connect the transistors must shrink as well. The problem, though, is that the smaller the cross section of a wire, the tougher it is to push an electrical signal through. Capacitance between extremely thin wires can add to the trouble. "The transistors are getting faster, but the wires are getting slower—and that's a prescription for disaster," says Kevin Martin of the Georgia Institute of Technology, who helps to direct the Interconnect Focus Center, an entity created to avert that disaster. Based at Georgia Tech, the center encompasses research at five other universities and is part of the larger Technology Focus Center research program, launched in 1998 with $10 million annual funding per center from the Semiconductor Industry Association's member companies and other groups.

The semiconductor industry has high hopes for the interconnect program. Right now the best commercial interconnects are copper wires, introduced into microchips in late 1998. But although copper is a vast improvement over aluminum interconnects, Martin says, the metal simply won't scale down sufficiently. For example, the intrinsic switching time for transistors having 100-nanometer gate lengths (circuit features referring to distances that electrons must travel) is on the order of 0.1 picosecond, 70 times faster

Technology & Business

Q&A_MARK MELLIAR-SMITH

The Route to Finer Lines

Physics may soon put an end to the rapid pace at which manufacturers can double a chip's speed. Today's one-gigahertz microprocessors have up to 20 million transistors and circuit features (specifically, gate lengths) only 140 nanometers long. They are born out of optical lithography using a light source with a wavelength of 248 nanometers. Light shining through a glass mask (essentially a stencil of a chip's features) projects the circuit pattern onto a silicon wafer coated with photoresist, an organic film that hardens when exposed to light. The shorter the wavelength of light projecting through the mask, the smaller the features on the chip.

But etching features much smaller than 100 nanometers by means of optical lithography is a whole new ball game, requiring novel photoresist materials (their sensitivity depends on the wavelength of light). And by the time chips featuring 70 nanometers or smaller are on deck, optical lithography may have to be put out to pasture altogether. Still, Mark Melliar-Smith, president and CEO of the semiconductor research consortium International SEMATECH, expects three to 10 gigahertz logic chips containing five billion transistors to be in production by 2014—one way or another. *—D.P.*

Is the end in sight for chip patterning by optical lithography?

One-hundred-ninety-three-nanometer optical lithography (which can produce transistors with 100-nanometer gates) is about 12 months away from manufacture. Beyond are several alternatives to get down to 50 nanometers, which, according to the International Technology Roadmap for Semiconductors, is about a decade away.

So what's the path from 193- to 50-nanometer lithography?

We have three different choices, each of which has significant technical challenges to be solved. The first, 157-nanometer optical lithography, uses a shorter wavelength of light—essentially more of the same of what we've been doing—but we'll have to find new photoresists and solve some other problems as well. The second one is electron projection lithography (EPL), of which Lucent's SCALPEL is the embodiment in the U.S. That has a different set of problems, including keeping the mask perfectly clean and getting the throughput up to levels comparable to those of optical lithography. The final one is extreme ultraviolet lithography (EUV), using an 11- to 13-nanometer radiation source, which requires special mirrors, a complicated new laser and thin-layer imaging techniques because, at this wavelength, materials are almost all opaque.

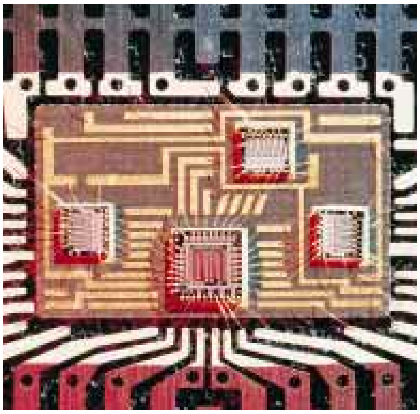
Do you fear that you're spreading yourselves too thin?

Having more than one choice gives you the opportunity to hedge your bets. Frankly, though, the two critical reasons we're pursuing all three technologies are that, one, all of them have significant risks, and we don't at this point know which is likely to be the most successful. And second, all three technologies have significant commercial support.

Who's winning so far?

EPL and the 157-nanometer optical lithography should be available in terms of an alpha-chip manufacturing tool within two years. At that point, we can fly them off against each other. EUV may be a little later but has the potential for the highest resolution, and this is important. For instance, 157-nanometer optical lithography only enables us to go 25 percent further down in size than we can today—that's a relatively short life span. But EPL and EUV offer the opportunity to go down several generations.

COURTESY OF SEMATECH



SPEED BUMPS: Interconnects, such as those between integrated-circuit components, could slow future computers.

than the response time of a typical one-millimeter-long copper interconnect wire. And the pressure is on—the International Technology Roadmap calls for chips with 100-nanometer gate lengths next year.

Leading the race for new interconnects are optical ones—replacing wires with fiber-optic cables that are resistance-free. Optics are ideal for high-bandwidth applications and are not constrained by long distances, unlike wire interconnects. Research at the Massachusetts Institute of Technology is focusing on sending signals between transistors on the chip itself, whereas David A. B. Miller, an electrical engineer at Stanford University, has directed his efforts at enabling separate chips to talk to one another at the necessary speed without having to be crammed closely together. "Using optics instead of wires is like being able to put in a 1,000-lane highway where you previously had a one-lane freeway," Miller remarks.

There are two main approaches to optical interconnects, albeit with myriad variations. One is transmitting light beams, generated by five- to 20-micron-high vertical cavity-surface-emitting lasers, or VCSELs, down waveguides built onto the chips. The other paradigm is based on freespace optics. Light from an external source can be reflected by tiny structures called quantum-well light modulators, which rapidly switch on and off in response to small voltages. Alternatively, patterns of light generated on one chip by VCSELs can be imaged on the other chip by a lens. "The second chip behaves like your retina," Miller explains. Though not yet ready for prime time, optical interconnects have been successfully demonstrated at several universities.

Just out of the gate, so to speak, is wireless-interconnect technology using radio-frequency (RF) signals. Various groups are working on this concept, including M. C. Frank Chang of the University of California at Los Angeles under the auspices of the Interconnect Focus Center. One example of how RF interconnects would work was presented in March by Kenneth K. O of the University of Florida and graduate students Brian A. Floyd and Kihong Kim at the International Solid-State Circuits Conference. They delivered a paper on the use of RF signals in massively parallel computers. With such large computer systems, maintaining a constant clock signal throughout numerous microprocessors becomes difficult. O's group hopes to get around that by broadcasting a clock signal from one IC to others using microwaves. One design integrates millimeter-size receivers and antennae on each IC in a multichip module. "By propagating the signal at the speed of light, we're trying to reduce the clock skew," O says. "You could send a wave down to a multichip module and provide equal clock phase to a very large area."

The group recently demonstrated on-chip wireless transmission and reception of a 7.4-gigahertz clock signal. O believes the same technology could be modified for data transfer between chips as well. Not surprisingly, the biggest antagonist to wireless interconnects is noise. Both the chip's silicon substrate and the switching of the transistors themselves degrade and taint the radio signal. The materials in chips "are just not very friendly to radio reception," O says. Whether optics or RF, researchers will undoubtedly find ways to keep traffic moving on tomorrow's computer systems. *—David Pescovitz*

DAVID PESCOVITZ is a contributing editor to Wired *and writes frequently for* Scientific American. *He is based in Oakland, Calif.*

Chilly Crystals

Thermoelectrics could double computer speeds

Another trick that could speed up computers is the use of semiconducting, thermoelectric materials to cool microprocessor chips. Unlike most metals, which become hot when an electric current passes through them, these substances have the ability to carry away heat while conducting electricity. Since the 1950s thermoelectric materials, fashioned into miniature heat pumps, have chilled solid-state lasers, infrared detectors and other electronic devices, which tend to run best cold. Unfortunately, the lowest temperature achieved by existing materials hovers around –50 degrees Celsius, a drop not large enough to justify routine use of these expensive minirefrigerators in today's computers.

Now a team led by Mercouri G. Kanatzidis, a chemist at Michigan State University, has concocted a new compound that can beat out the existing competition by cooling to a record –100 degrees C and make faster chips a reality. "This new technology has the potential to increase computer speeds by 100 percent simply by cooling the chip," Kanatzidis notes.

The new crystal—a mixture of bismuth, tellurium and cesium—is a breakthrough because it enhances the thermoelectric effect by being both a good conductor and thermal insulator. But a thermoelectric cooler cannot be made yet, Kanatzidis reveals, because his team has only developed one of the necessary conductors. For heat pumps to work, two different material types (technically called *n*- and *p*-types) are needed to create a temperature difference.

Kanatzidis believes that a cooling device made from his new material could be sandwiched between a microprocessor and a heat exchanger, such as a fan. Heat, generated from the superfast chip sitting on the surface of the semiconductor, would travel from top to bottom and be dispersed by the fan. Direct cooling of the chip would translate into higher speed because the mobility of the electrons would increase in a chillier environment.

Speed freaks, though, will have to keep it in the slow lane for a while longer. A workable prototype for the general market will take several more years to develop. Still, since the story broke out, "people have been calling me and asking when I can ship them 2,000 of these things," Kanatzidis says with a laugh. "We have a material, not a device." *—Diane Martindale*

Cyber View

DVDs: Cease and DeCSS?

Back in 1990, organized Net activism began with an unfair prosecution when, as one of a series of raids on (mostly) teenaged hackers, federal investigators swooped down on a small publishing company based in Austin, Tex., that produced role-playing games. The Steven Jackson Games case was one inspiration behind the founding of the Electronic Frontier Foundation and the coming together of the Net as a community that believed itself and its values to be under threat. So when news broke late last year that a 16-year-old Norwegian boy named Jon Johansen and his father had been arrested at the behest of the movie studios because of a bit of software they had posted to the Net, it all seemed awfully familiar.

The software is known as DeCSS: it makes it possible to view DVD movies on computers running the free operating system Linux. Johansen didn't write it, but he was among the first to post it, on the Web site owned by his father.

CSS stands for content scrambling system, and its mission is to stop unauthorized copying. Basically, it's an encryption system that ensures that the data can be read only by a player that contains the necessary decryption keys. The problem is that it isn't easy to disseminate an encryption system on millions of devices and have it stay secret. In October 1999 someone cracked CSS and posted the results on the Net. The point was not to enable piracy, say DeCSS supporters such as the organizers of the OpenDVD site, but to allow Linux users to play their legally purchased DVDs, because there is no commercial software available to play discs on systems other than Mac- and Windows-based PCs. Point taken, although this does not explain why, on February 22, 2000, when I went searching for copies of DeCSS for Linux, I found a Windows version (which I, of course, promptly downloaded before it could disappear forever).

Other "ripping" methods—that is, software to enable you to extract the files from a disc—have been available before. But DeCSS has an important difference: because it actually cracked the encryption system, it was arguably illegal under the Digital Millennium Copyright Act. Enacted in 1998 to strengthen copyright rules on the Internet, the act defined as criminal the removal of copy-protection mechanisms. And so the suits began.

Four cases are working their way through the courts: Johansen's criminal case in Norway; a case brought in San Jose, Calif., by the DVD Copy Control Association claiming trade-secret violations by people who posted DeCSS or other material on their Web sites; and twin cases brought against three individuals in

DAVID SUTER

New York State and Connecticut by the Motion Picture Association of America on behalf of eight major movie studios.

The Norwegian and Connecticut cases are still pending. In the California case, the judge issued a preliminary restraining order blocking the defendants from publishing DeCSS on the Web. (The ruling is being appealed.) In New York, the judge ruled in favor of the movie studios, again blocking publication of the software. In this instance, the complaint has been amended to include providing Web links to the software; that issue has not been decided yet.

DeCSS supporters are right to argue that CSS doesn't prevent wholesale commercial piracy. Bit-by-bit professional copies of DVDs include CSS in all its glory, so pirated discs will play perfectly. Pirating single copies of DVDs—the kind of activity that CSS might stop—is currently not practical. It is time-consuming and most likely more expensive than buying the disc. On today's dial-up connections, one side of a DVD, containing roughly three gigabytes, would take more than 14 hours to download, not to mention all that storage space needed on your computer. Some people will go through the trouble of downloading, but such avid fans will almost definitely still go see the movie in theaters and will probably buy it on DVD as well—its playback is certainly more impressive on a 32-inch television than on a computer monitor. High-speed access through cable modems and DSL will eventually become ubiquitous enough to make this type of downloading viable. But the answer for studios is to compete more effectively with downloaders, by either dropping prices or adding value to the physical package.

Although it makes sense to prosecute wholesale piracy, it makes no sense whatsoever to refuse to produce software to allow people to play legally acquired discs on devices they own and then prosecute them if they write their own software. It makes even less sense to prosecute people for doing what the Web was built for: posting and linking to useful information.

There is an additional reason why DVD is so hated: it is deliberately crippled technology. It's not just Linux users who can't play their discs. Movie studios were so horrified by the thought of losing control over their carefully timed release schedules that even though they wanted to save money by making and marketing the same discs everywhere, they designed a cryptographic system that divides the world into six encoding regions. It ensures that American discs will not play on British players, and vice versa.

The world is changing around them. British moviegoers, for example, are fed up with having to wait six months and then pay 60 percent more to see the latest U.S. releases. E-commerce sites enable anyone anywhere in the world to buy U.S. discs (which are typically not only cheaper but are released sooner and stuffed with more extras). DVD players that have been hacked to play discs from all six world regions are readily available in London stores—even in leading supermarket chain Tesco, which has begun advertising machines that can be hacked just by pushing a few buttons on the remote control. A full-scale rebellion seems to be under way. *—Wendy Grossman*

WENDY GROSSMAN, a regular contributor based in London, described mobile Internet access in the March issue.

Asteroids have become notorious as celestial menaces but are best appreciated in a positive light, as surreal worlds bearing testimony to the origin of the planets

The Small Planets

by Erik Asphaug

Growing up in the Space Age, my friends and I would sometimes play the gravity game. One of us would shout, "Pretend you're on the moon!" and we'd all take the exaggerated slow strides we'd seen on television. "Pretend you're on Jupiter!" another would say, and we'd crawl on our hands and knees. But no one ever shouted, "Pretend you're on an asteroid!" In that pre-*Armageddon* era, who knew what "asteroid" meant? Now a grown-up who studies asteroids for a living, I still don't know how to respond.

Although we haven't seen any of the largest asteroids up close, they probably resemble shrunken, battered versions of the moon. In their weaker gravity, visiting astronauts would simply take longer strides. But below a few dozen kilometers in diameter, gravity is too feeble to press these so-called minor planets into even an approximately round shape. The smallest worlds instead take on a carnival of forms, resembling lizard heads, kidney beans, molars, peanuts and skulls. Because of their irregularity, gravity often tugs away from the center of mass; when added to the centrifugal forces induced by rotation, the result can seem absurd. Down might not be down. You could fall up a mountain. You could jump too high, never to return, or launch yourself into a chaotic (though majestically slow) orbit for days before landing at an unpredictable location. A pebble thrown forward might strike you on the head. A gentle vertical hop might land you 100 meters to your left or even shift the structure of the asteroid underfoot. Even the most catlike visitor would leave dust floating everywhere, a debris "atmosphere" remaining aloft for days or weeks.

These aspects of asteroid physics are no longer only theoretical curiosities or a game for children. Space missions such as the Near Earth Asteroid Rendezvous (NEAR), the first probe to go into orbit around a minor planet, are dramatically modernizing our perception of these baffling objects. But in spite of careful observations and the occasional proximity of these bodies to Earth, we know less about asteroids (and their relatives, the comets) than we knew about the moon at the dawn of space exploration. Minor planets exhibit a delicate interplay of minor forces, none of which can be readily ignored and none of which can be easily simulated in a laboratory on Earth. Are they solid inside, or aggregate assemblages? What minerals are they composed of? How do they survive collisions with other small bodies? Could a lander or astronaut negotiate an asteroid's weird surface?

Half-Baked Planets

My graduate studies began during the Bush administration, when asteroids were mere dots—a thousand points of light known to orbit primarily in a belt between Mars and Jupiter. A few lesser populations were known to swoop closer to Earth, and then there were comets in the Great Beyond. From periodic variations in color and brightness, asteroids were inferred to be irregular bodies ranging in size from a house to a country, rotating every several hours or days. More detailed properties were largely the stuff of scientific imagination.

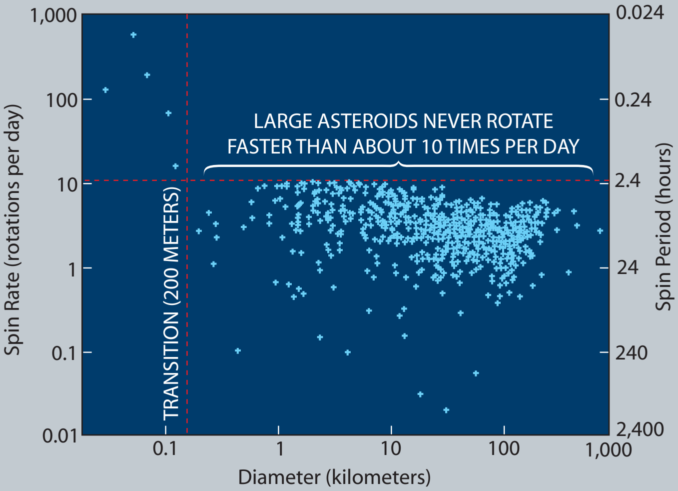
Asteroids residing closer to Mars and Earth commonly have the spectra of rocky minerals mixed with iron, whereas asteroids on the Jupiter side are generally dark and red, suggesting a primitive composition only coarsely differentiated from that of the primordial nebula out of which the planets began to coalesce 4.56 billion years ago [*see illustration on page 48*]. This timing is precisely determined from analysis of lead isotopes—the products of the radioactive decay of uranium—in the oldest grains of the most primitive meteorites. In fact, meteorites have long been suspected to derive from asteroids. The spectra of certain meteorites nearly match the spectra of certain class-

JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY AND NASA

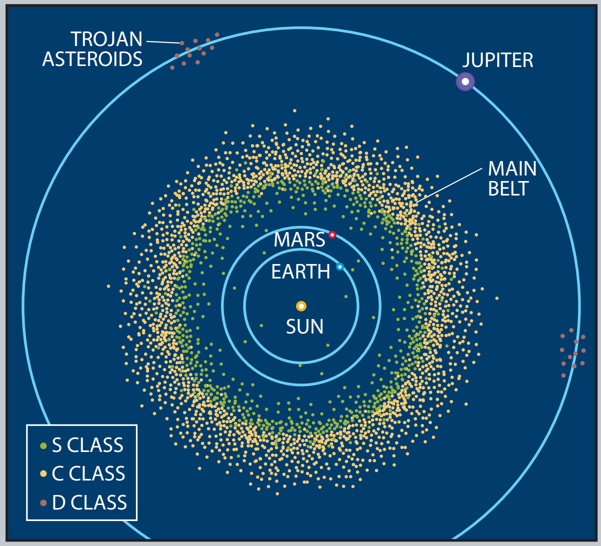
GIANT PAW PRINT is a strange crater on the asteroid Eros, so dubbed by scientists now studying this 33-kilometer-long space rock with the NEAR space probe (*center of lower image*). On the other side of the body is a youthful, saddle-shaped gouge (*left of upper image*) full of unexplained markings. Through images such as these, asteroids are now turning from astronomical objects—mere points of light—into geologic objects—whole worlds whose exploration has only begun.

Types of Asteroids

Where They Roam



TWO GROUPS OF ASTEROIDS emerge on a plot of their rotation rates (*vertical axis*) versus size (*horizontal axis*). No known asteroid larger than 200 meters across rotates faster than once every 2.2 hours. The cutoff is easy to explain if these asteroids are piles of rubble that fly apart if spun too fast. Smaller asteroids, which can turn once every few minutes, must be solid rocks. The transition probably arose because of collisions.



MAIN ASTEROID BELT lies between the orbits of Mars and Jupiter, but stragglers cross Earth's orbit (and sometimes collide with Earth) or revolve in sync with Jupiter (in two groups known as the Trojan asteroids). The inner main belt consists mainly of stony or stony-iron asteroids (S class); farther out the asteroids are darker, redder and richer in carbon (C class and D class).

LAURIE GRACE; SOURCE: PETR PRAVEC *Academy of Sciences of the Czech Republic (from sunkl.asu.cas.cz/~asteroid/3FRAs)*

es of asteroids. We therefore have pieces of asteroids in our possession.

Many astronomers used to think that telescope observations, combined with meteorite analysis, could substitute for spacecraft exploration of asteroids. Although the puzzles proved more stubborn than expected, researchers have been able to piece together a tentative outline of solar system history. For the planets to have accreted from a nebula of dust and gas, there had to be an initial stage in which the first tiny grains coagulated into growing bodies known as planetesimals. These became the building blocks of planets. But in the zone beyond Mars, gravitational resonances with massive Jupiter stirred the cauldron and prevented any body from growing larger than 1,000 kilometers across—leaving unaccreted remnants to become the present asteroids.

The largest of these would-be planets nonetheless accumulated enough internal heat to differentiate: their dense metals percolated inward, pooling and perhaps forming cores, leaving behind lighter rocky residues in their outer layers. Igneous activity further metamorphosed their rock types, and volcanoes erupted on some. Although none grew large enough to hold on to an atmosphere, hydrated minerals found in some meteorites reveal that liquid water was often present.

Encounters among the planetesimals became increasingly violent as Jupiter randomized the orientation and ellipticity of their orbits. Instead of continuing to grow, the would-be planets were chiseled or blasted apart by mutual collisions. Their pieces often continued to orbit the sun in families with common orbital characteristics and related spectra. Many asteroids and meteorites are the rock- or metal-rich debris of these differentiated protoplanets. Other asteroids (and most comets) are more primitive bodies that for various reasons never differentiated. They are relics from the ur-time before planets existed.

The Sky Is Falling

A decade ago no asteroid had been imaged in any useful detail, and many astronomers had trouble taking them seriously. The first asteroids, discovered in the early 1800s, were named in the grand mythological manner. But with the tenth, the hundredth and the thousandth, asteroids began taking on the names of their discoverers, and then of discoverers' spouses, benefactors, colleagues and dogs. Now, after a century of near-neglect, serious interest in asteroids is waxing as new observations transform them from dim twinkles in the sky into mind-boggling landforms. For this, asteroid scientists can thank National Aeronautics and Space Administration administrator Daniel S. Goldin and the dinosaurs.

Goldin's "faster, better, cheaper" mantra has been a boon to asteroid science, because a visit to a tiny neighbor is both faster and cheaper than a mission to a major planet. The specter of fiery death from above has also focused minds. The discovery of the Chicxulub crater in the Yucatán vindicated the idea that the impact of an asteroid or comet 65 million years ago extinguished well over half the species on Earth [see "An Extraterrestrial Impact," by Walter Alvarez and Frank Asaro; Scientific American, October 1990; "Collisions with Comets and Asteroids," by Tom Gehrels; Scientific American, March 1996].

A repeat is only a matter of time, but when? Until we completely catalogue all significant near-Earth asteroids—a job we have just begun—poker analogies must suffice. (We will never completely catalogue the comet hazard, because each comet visits the inner solar system so rarely.) The chance of a global calamity in any year is about the same as drawing a royal flush; your annual chance of dying by other means is about the same as drawing three of a kind. None of us is remotely likely to die by asteroid impact, yet even scientists are drawn to the excitement of apocalypse, perhaps too often characterizing asteroids by their potential explosive yield in megatons instead of by diameter. Our professional dilemma is akin to notoriety in art: we want asteroids to be appreciated for higher reasons, but notoriety pays the bills.

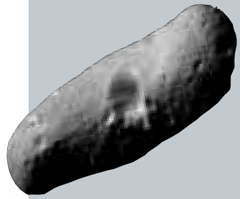
Egged on by this nervous curiosity, we are entering the golden age of comet and asteroid exploration. Over a dozen have been imaged [*see box on next page*], and each new member of the menagerie is welcomed with delight and perplexity. They are not what we expected, to say the least. Small asteroids were predicted to be hard and rocky, as any loose surface material (called regolith) generated by impacts was expected to escape their weak gravity. Aggregate small bodies were not thought to exist, because the slightest sustained relative motion would cause them to separate.

Reduced to Rubble

But observations and modeling are proving otherwise. Most asteroids larger than a kilometer are now believed to be composites of smaller pieces. Those imaged at high resolution show evidence for copious regolith despite the weak gravity. Most of them have one or more extraordinarily large craters, some of which are wider than the mean radius of the whole body. Such colossal impacts would not just gouge out a crater—they would break any monolithic body into pieces. Evidence of fragmentation also comes from the available measurements for asteroid bulk density. The values are improbably low, indicating that these bodies are threaded with voids of unknown size.

In short, asteroids larger than a kilometer across may look like nuggets of hard rock but are more likely to be aggregate assemblages—or even piles of loose rubble so pervasively fragmented that no solid bedrock is left. This rubble-pile hypothesis was first proposed two decades ago by Don Davis and Clark Chapman, both then at the Planetary Science Institute in Tucson, but they did not suspect that it would apply to such small diameters.

Shortly after the NEAR spacecraft flew by asteroid Mathilde three years ago on its way to Eros, the late planetologist



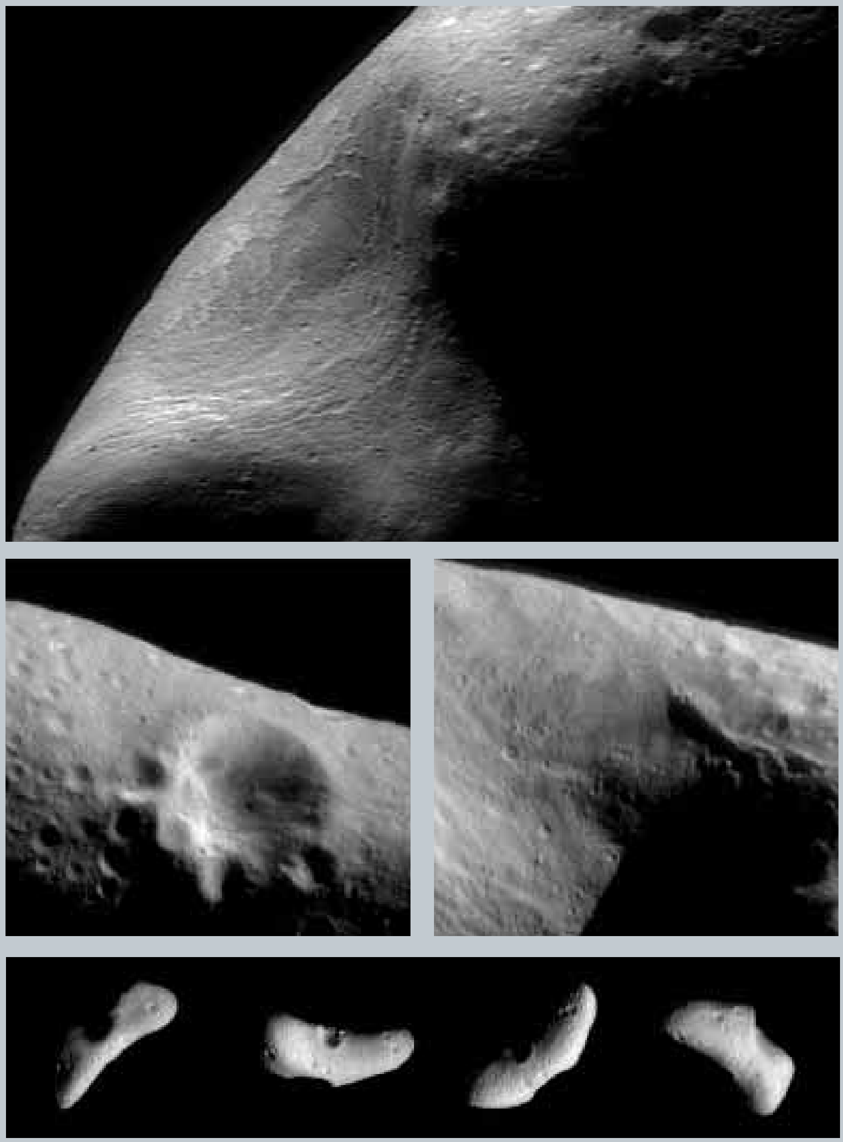
NEAR's Courtship with Eros

A Lovely Rock

Eros, currently orbited by the NEAR spacecraft, resembles a boat with a narrow bow, a wide stern and a prominent crater on the concave deck. Copious mounded and blocky debris around this crater show the influence of gravity during its formation. A boulder is inside, stopped halfway; it can't seem to figure out which way is down. Another prominent divot, on the opposite side, is so big that it is part of Eros' overall shape. If it is of impact origin, as is probable, its formation must have cracked Eros into a few great pieces mantled in lesser fragments and debris.

The name "Eros" befits a coy flirtation with Earth. Unfortunately, this love affair may end in sorrow. Paolo Farinella of the University of Trieste and Patrick Michel of Nice Observatory have calculated that Eros has a 5 percent chance of colliding with Earth in the next one billion years, with an intensity exceeding that which extinguished the dinosaurs.

NEITHER SOLID ROCK NOR DUST BUNNY, Eros is a conglomerate of several major pieces crosscut by faults, scarps and ridges. The largest structure is a smooth, striated gouge that is nearly devoid of craters (*below*). The most prominent crater—the "paw print" six kilometers across—has massive deposits on its rim, which indicate that gravity dictated its formation (*center left*). A steep ridge, which runs parallel to the linear markings, suggests faulting in a coherent material (*center right*). The asteroid rotates once every five and a half hours (*bottom*).



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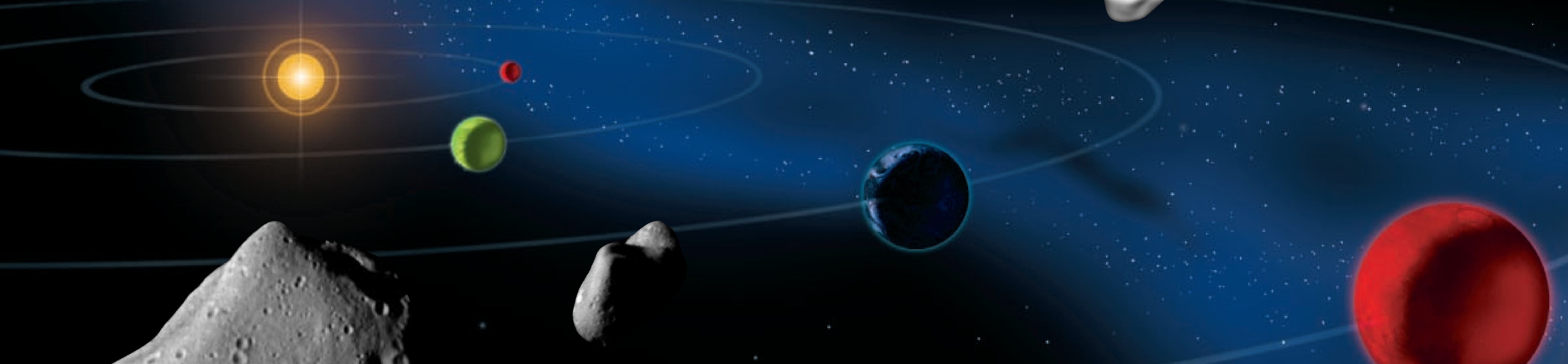
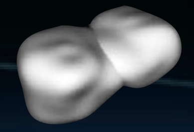
Asteroid Visitations

The Rock Concert

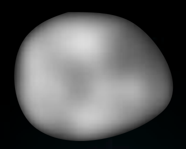




CASTALIA

Official catalogue number: **4769** Dimensions: **1.8 x 0.8 kilometers**
Density: **2.1 grams per cubic centimeter (surface)** Orbit type: **Earth crossing**
Spectral class: **S** Rotation: **4 hours**

Castalia was the first asteroid ever to be imaged. In August 1989 it flew within 11 lunar distances of Earth—still too far for optical telescopes but close enough for radar. Steven J. Ostro and his group at the Jet Propulsion Laboratory targeted the body with powerful and precise beams from the world's largest radio telescope, in Arecibo, Puerto Rico. Castalia's peanut shape suggests two 800-meter pieces resting together despite the very weak gravity. Radar echoes from other Earth-crossing asteroids now tell us that contact-binary configurations are common.



VESTA

Official catalogue number: **4** Dimensions: **525 kilometers in diameter**
Density: **3.3 grams per cubic centimeter** Orbit type: **Main belt**
Spectral class: **V** Rotation: **5.34 hours**

Only Vesta among the large asteroids has a surface of basaltic rock from ancient lava flows. In the distant past, it evidently differentiated into layers and underwent many of the same geologic processes as early Mars or Earth. Dozens of Vesta-like bodies presumably existed at one time but were broken apart into families of smaller asteroids. Iron meteorites are thought to come from the cores of these shattered worlds and igneous meteorites from their crusts and mantles. In 1996 the Hubble Space Telescope obtained this image of Vesta, showing a huge crater 430 kilometers across. Perhaps a billion years old, this crater might be the source of the small V-type asteroids observed today.

MATHILDE

Official catalogue number: **253** Dimensions: **66 x 48 x 46 kilometers**
Density: **1.3 grams per cubic centimeter** Orbit type: **Main belt**
Spectral class: **C** Rotation: **17.4 days**

On its way to Eros, NEAR made the first spacecraft encounter with a primitive C-type asteroid. This blacker-than-coal spheroid, the largest asteroid yet visited and one of the slowest rotators, follows an eccentric orbit extending to the outer reaches of the main belt. The spacecraft's trajectory was slightly deflected by Mathilde, telling us its mass. The implied density is less than half that of the closest matching meteorites, carbonaceous chondrites, so if Mathilde is made of the same material, it must be very loosely packed. The same is true of another C-type asteroid, Eugenia, recently studied using a ground-based telescope equipped with sophisticated adaptive optics.

The giant craters are amazing. Several are wider than Mathilde's average radius, yet none have rims or ejecta deposits, which are associated with large craters on other worlds. Also, none of the craters have been degraded by subsequent cratering; we can't even tell which impact happened first or last. It is as though some deity has come and taken tidy bites from a cosmic apple.

EROS

Official catalogue number: **433**
Dimensions: **33 x 13 x 13 kilometers**
Density: **2.7 grams per cubic centimeter**
Orbit type: **Near Earth**
Spectral class: **S**
Rotation: **5.27 hours**

GASPRA

Official catalogue number: **951** Dimensions: **19 x 12 x 11 kilometers**
Density: **Not known** Orbit type: **Main belt (Flora family)**
Spectral class: **S** Rotation: **7.04 hours**

Gaspra was the first asteroid visited by a spacecraft: Galileo flew by in 1991 on its way to Jupiter. Some have argued that its half-dozen large concavities are not craters but facets formed when Gaspra broke off from its parent asteroid. On the other hand, in the weak, irregular gravity of Gaspra, the largest impact craters would naturally take on such a flat, lopsided shape.

TOUTATIS

Official catalogue number: **4179** Dimensions: **4.5 by 2.4 by 1.9 kilometers**
Density: **2.1 grams per cubic centimeter (surface)** Orbit type: **Earth crossing**
Spectral class: **S** Rotation: **Two separate periods (5.41 and 7.35 days)**

Since the first observations of Castalia, better opportunities for radar detection of asteroids have presented themselves, most notably for asteroid Toutatis. Strongly influenced by Earth's gravity, its orbit is chaotic. Also, it wobbles with two types of motion that combine to create nonperiodic rotation. A visitor would never see the same horizon twice. On September 29, 2004, Toutatis will come within four lunar distances, whereupon it will be visible with binoculars.

IDA & DACTYL

Official catalogue number: **243**
Dimensions: **56 x 24 x 21 kilometers** Density: **About 2.5 grams per cubic centimeter**
Orbit type: **Main belt (Koronis family)** Spectral class: **S** Rotation: **4.63 hours**

Two years after visiting Gaspra, Galileo flew by this main-belt asteroid. An unexpected gem from this encounter was the discovery of Dactyl—the first known asteroid satellite, a mere 1.4 kilometers in diameter. The Galileo team used Dactyl's orbit to calculate Ida's mass. The implied density is much lower than that of the most closely related type of meteorite, ordinary chondrites, so Ida must be of different composition or else porous. Some believe that Dactyl agglomerated out of slow ejecta from one of Ida's largest craters, although this would have been very difficult to achieve dynamically. Daniel Durda of the Southwest Research Institute in Boulder, Colo., showed that Dactyl and Ida could have formed as a pair a billion or more years ago, when Ida's parent body was disrupted. But it is hard to explain how Dactyl could have survived for so long without being destroyed.

SCOTT HUDSON *Washington State University* (*Castalia*); BEN H. ZELLNER *Georgia Southern University* AND NASA (*Vesta*); JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY AND NASA (*Eros* and *Mathilde*); NASA/JET PROPULSION LABORATORY (*Gaspra*); NASA/JPL (*Ida*)

Flintstone or Rubble?

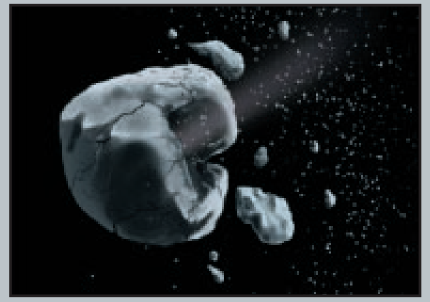
Really Deep Impacts

RUBBLE-PILE ASTEROID, whose fragmented structure bears the scars of all its past collisions, is struck again by a smaller asteroid at high speed. Such bang-ups are fairly common.

In the aggregate body the blast remains confined to the local area. Within a few minutes, the smallest, fastest debris has escaped. The larger fragments drift slowly outward.

Some large pieces escape; some return. A few days later things have settled down. Over time the wound will be covered in debris thrown out by bombardment and other processes.

SOLID ASTEROID, a monolithic chunk of rock, responds very differently to a collision than the rubble pile does—just as a log responds differently to the blow of an ax than a mound of wood chips does.



The shock wave propagates deep into the interior, blasting apart the whole body. The fastest ejecta are soon gone, leaving larger fragments to undergo a gentle gravitational dance for hours.

Many of these pieces come to rest in a pile of rubble. Because it is so easy to turn a solid rock into a rubble pile, few asteroids larger than a few hundred meters across are still solid.

Eugene M. Shoemaker (for whom NEAR has been renamed) realized that the huge craters on this asteroid and its very low density could only make sense together: a porous body such as a rubble pile can withstand a battering much better than an integral object. It will absorb and dissipate a large fraction of the energy of an impact; the far side might hardly feel a thing. A fair analogy is a bullet hitting a sandbag, as opposed to a crystal vase.

What about the jagged shapes of most asteroids? Intuition tells us that dramatic topography implies solidity. But first glances can deceive. When measured relative to the fun-house gravity, no regional slope on any imaged asteroid or comet exceeds a typical angle of repose (about 45 degrees), the incline at which loose debris tumbles down. In the steepest regions, we do see debris slides. In other words, small bodies could as well be made of boulders or even sand and still hold their shape. Dunes, after all, have distinct ridges yet are hardly monolithic. Rapid rotation would contribute to an elongated, lumpy appearance for a rubble pile.

Direct support for the rubble-pile hypothesis emerged in 1992, when comet Shoemaker-Levy 9 strayed too close to Jupiter and was torn into two dozen pieces. Two years later this "string of pearls" collided with the giant planet [see "Comet Shoemaker-Levy 9 Meets Jupiter," by David H. Levy, Eugene M. Shoemaker and Carolyn S. Shoemaker; Scientific American, August 1995]. According to a model I developed with Willy Benz of the University of Bern, the comet could have disassembled as it did only if it consisted of hundreds of loose grains in a slow cosmic landslide. As the comet was stretched by Jupiter's tides, the grains gravitated into clumps much like water beading in a fountain. From this breakup we proposed that comets are likely to be granular structures with a density around two thirds that of water ice. What applies to comets might apply to asteroids as well.

When Nothing Matters, Everything Matters

Yet the rubble-pile hypothesis is conceptually troublesome. The material strength of an asteroid is nearly zero, and gravity is so low you are tempted to neglect that, too. What's left? The truth is that neither strength nor gravity can be ignored. Paltry though it may be, gravity binds a rubble pile together. And anyone who builds sand castles knows that even loose debris can cohere. Oft-ignored details of motion begin to matter: sliding friction, chemical bonding, damping of kinetic energy, electrostatic attraction and so on. (In fact, charged particles from the sun can cause dust at the surface to levitate.) We are just beginning to fathom the subtle interplay of these minuscule forces.

The size of an asteroid should determine which force dominates. One indication is the observed pattern of asteroidal rotation rates. Some collisions cause an asteroid to spin faster; others slow it down. If asteroids are monolithic rocks undergoing random collisions, a graph of their rotation rates should show a bell-shaped distribution with a statistical "tail" of very fast rotators. If nearly all asteroids are rubble piles, however, this tail would be missing, because any rubble pile spinning faster than once every two or three hours (depending on its bulk density) would fly apart. Alan Harris of the Jet Propulsion Laboratory in Pasadena, Calif., Petr Pravec of the Academy of Sciences of the Czech Republic in Prague and their colleagues have discovered that all but five observed asteroids obey a strict rotation limit [*see illustration on page 48*]. The exceptions are all smaller than about 150 meters in diameter, with an abrupt cutoff for asteroids larger than about 200 meters.

The evident conclusion—that asteroids larger than 200 meters across are multicomponent structures or rubble piles—agrees with recent computer modeling of collisions, which also finds a transition at that diameter. A collision can blast a large asteroid to bits, but those bits will usually be moving slower than their mutual escape velocity (which, as a rule of thumb, is about one meter per second, per kilometer of radius). Over several hours, gravity will reassemble all but the fastest pieces into a rubble pile [*see illustration above*]. Because collisions among asteroids are relatively frequent, most large bodies have already suffered this fate. Conversely, most

small asteroids should be monolithic, because impact fragments easily escape their feeble gravity.

Qualitatively, a "small" asteroid sustains dramatic topography, and its impact craters do not retain the debris they eject. It looks like a battered bunker in a war movie. A "large" asteroid is an assemblage of smaller pieces that gravity and random collisions might nudge into a rounded or, if spinning, an elongated shape. Its craters will have raised rims and ejecta deposits, and its surface will be covered in regolith. But this size distinction is not straightforward. Asteroid Mathilde could be considered small, as it has no visible rims or ejecta deposited around its enormous craters, or large, as it is approximately spheroidal. Tiny Dactyl could seem large, also being spheroidal and sustaining such well-developed craters. The ambiguity is a sign that the underlying science is uncertain.

Shock Value

Given that geophysicists are still figuring out how sand behaves on Earth and how landslides flow, we must be humble in trying to understand conglomerate asteroids. Two approaches are making inroads into one of their key attributes: how they respond to collisions.

Derek Richardson and his colleagues at the University of Washington simulate asteroids as piles of discrete spheres. Like cosmic billiards on a warped pool table—the warp being gravity—these spheres can hit one another, rebound and slow down because of friction and other forms of energy dissipation. If balls have enough collisional energy, they disperse; more commonly, some or all pile back together. Richardson's model is particularly useful for studying the gentle accretionary encounters in the early solar system, before relative velocities started to increase under the gravitational influence of nascent Jupiter. It turns out to be surprisingly difficult for planetesimals to accrete mass during even the most gentle collisions.

High-speed collisions, more typical of the past four billion years, are more complicated because they involve the minutiae of material characteristics such as strength, brittle fracture, phase transformations, and the generation and propagation of shock waves. Benz and I have developed new computational techniques to deal with this case. Rather than divide a target asteroid into discrete spheres, we treat it as a continuous body, albeit with layers, cracks, or networks of voids.

In one sample simulation, we watch a 6,000-ton impactor hit billion-ton Castalia at five kilometers per second. This collision releases 17 kilotons of energy, the equivalent of the Hiroshima explosion—and enough to break up Castalia. We simulate Castalia as a two-piece object held together by gravity. The projectile and an equal mass of Castalia are vaporized in milliseconds, and a powerful stress wave is spawned. Because the shock wave cannot propagate through vacuum, it rebounds off surfaces, including the fracture between the two pieces of the asteroid. Consequently, the far piece avoids damage. The near piece cracks into dozens of major fragments, which take hours to disperse; the largest ones eventually reassemble. This outcome is very sensitive to what we start with. Other initial configurations and material parameters (which are largely unknown) lead to vastly different outcomes. Asteroids that start off as rubble piles, for example, are hard to blast apart.

Rendezvous with Eros

We can also work backward, inferring the rock properties of an asteroid by trying out different initial guesses and comparing the simulations with observations. As an example, I have worked with Peter Thomas of Cornell University to re-create the largest crater on Mathilde as precisely as possible: its diameter and shape (easy enough), its lack of fracture grooves or damage to existing craters (somewhat harder) and the absence of crater ejecta deposits (very hard).

If we assume that Mathilde was originally solid and monolithic, our model can reproduce the crater but predicts that the asteroid would have cracked into dozens of pieces, contrary to observations. If we assume that Mathilde was originally a rubble pile, as Shoemaker suggested, then our impact model easily matches the observations. Kevin Housen of the Boeing Shock Physics Lab and his colleagues have also argued that Mathilde is a rubble pile, although they regard the craters as compaction pits—

BRYAN CHRISTIE

like dents in a beanbag—rather than excavated features.

Understanding asteroid structure will be crucial for future missions. A rubble pile will not respond like a chunk of rock if we hope to gather material for a sample return to Earth or, in the more distant future, construct remote telescopes, conduct mining operations or attempt to divert a doomsday asteroid headed for Earth. The irregular gravity is also a problem; spacecraft orbits around comets and asteroids can be chaotic, making it difficult to avoid crashing into the surface, let alone point cameras and instruments. NEAR is therefore conducting most of its science a hundred kilometers or more away from Eros. At this distance the irregular, rapidly rotating potato exerts almost the same gravity that a sphere would. The spacecraft's deviation from a standard elliptical orbit will enable NEAR scientists to measure the density distribution within Eros.

Orbiting Eros at the speed of a casual bicyclist (corresponding to the low gravity), NEAR is beaming a torrent of data toward Earth. The primary objective is to clarify the link between asteroids and meteorites. Cameras are mapping the body to a few meters' resolution, spectrometers are analyzing the mineral composition, and a magnetometer is searching for a native magnetic field and for interactions with the solar field. Upcoming missions will probe asteroids and comets in ever greater detail, using a broader range of instruments such as landers, penetrators and sample returns [*see box at right*].

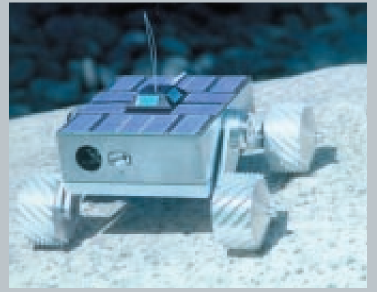
These discoveries will help plug a vast conceptual hole in astronomy. We simply don't understand small planetary bodies, where gravity and strength compete on sometimes equal footing. Asteroids are a balancing act, as serene as the moon yet of cataclysmic potential, large enough to hang onto their pieces yet too small to lose their exotic shape. Neither rocks nor planets, they are something of Earth and Heaven. SA

Upcoming Missions

The NEAR Future

Before any of us can set foot on an asteroid, minor planets must be poked and prodded just as the moon was before *Apollo 11* could land. To this end, several new missions will follow up the ongoing success of the Near Earth Asteroid Rendezvous.

Two will collect samples and bring them back to Earth. NASA's Stardust spacecraft was launched in February 1999 toward Comet Wild 2 and is expected to return in 2006 with a piece of the tail (some grains of precious dust). The Japanese space agency plans to launch the MUSES-C space probe in 2002 to collect material from the asteroid Nereus, where it will also release a NASA-built "hopper" that will jump across the surface like a flea [*see illustration below*]. Although it has wheels, it is anyone's guess whether the hopper will be able to obtain enough friction to drive.



NANOROVER will hop across the surface of the asteroid Nereus. (For plans to build your own model, see spaceplace.jpl.nasa.gov/muses3.htm on the World Wide Web.)

NASA/JET PROPULSION LABORATORY

The Comet Nucleus Tour, or Contour, has recently been selected for a 2002 launch and is scheduled to closely inspect two distinct cometary nuclei in 2003 and 2006 and perhaps a third in 2008. Another comet probe, the European Space Agency's Rosetta, should set out in 2003 and rendezvous in 2011 with Comet Wirtanen (a distant comet nudged toward the inner solar system by an encounter with Jupiter). It will also visit two small asteroids en route. Rosetta and its lander will watch as Wirtanen, moving from the outer solar system toward its closest approach to the sun, changes from a cold, quiet ice world into an eruptive, gas-shrouded spectacle.

The first mission to perform a geomechanical experiment on an asteroid will be Deep Impact, which, if all goes well, will blow a large crater in Comet Tempel 1 using a 500-kilogram copper projectile. How large? That depends on the comet's properties, which we hope to learn. A similar, though perhaps less dramatic, mission could perform seismic imaging of an asteroid's interior by firing a stream of "smart" bullets—shielded projectiles that each encapsulate an accelerometer and a radio transmitter. Each accelerometer would record not only its own brutal deceleration into the asteroidal surface, telling whether it struck fine powder or gravel or rock, but also the seismic signal from other bullets as they come slamming in over the course of one asteroid rotation. Together they would reveal the structure of the asteroid's interior, just as geologists have learned the internal structure of Earth by listening to earthquakes. —*E.A.*

The Author

ERIK ASPHAUG recalls his quarter-dropping days playing the video game Asteroids: "You get two big chunks and maybe two smaller chunks whenever you kill an asteroid. In truth you'll get hundreds of tiny, fast pieces and some larger pieces filling your screen with pesky debris." Besides his gaming ambitions, Asphaug gardens and plays guitar to his one-year-old son, Henry, and simulates asteroid collisions on a Cray T3E supercomputer. He is a researcher at the University of California, Santa Cruz. In recognition of his work, Asphaug was awarded the 1998 Urey Prize of the American Astronomical Society.

Further Information

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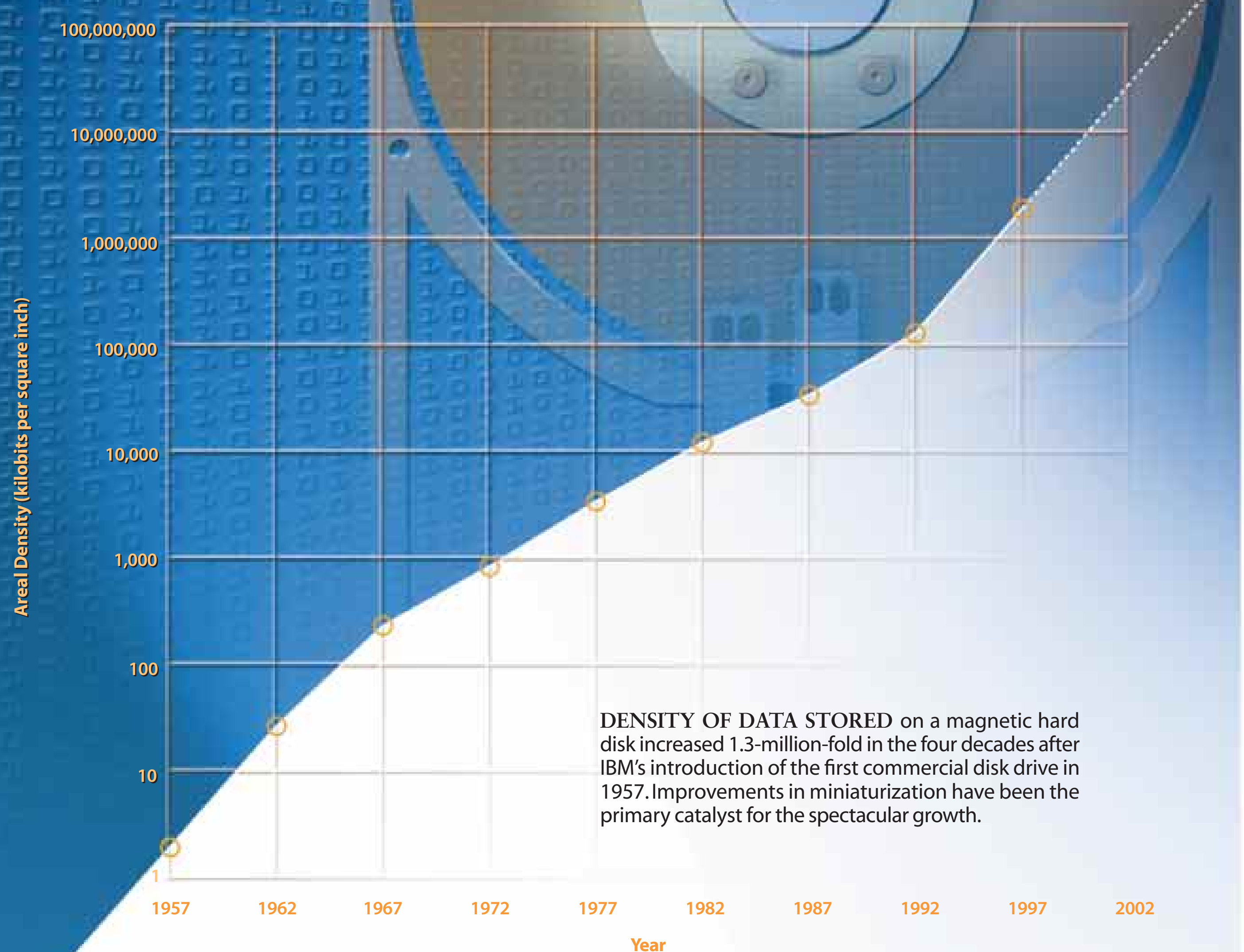
For updates on the Near Earth Asteroid Rendezvous mission, visit http://near.jhuapl.edu

For general information on near-Earth objects, go to http://neo.jpl.nasa.gov

The author's Web site is at http://planet.ucsc.edu

AVOIDING A DATA CRUNCH



DENSITY OF DATA STORED on a magnetic hard disk increased 1.3-million-fold in the four decades after IBM's introduction of the first commercial disk drive in 1957. Improvements in miniaturization have been the primary catalyst for the spectacular growth.

TOM DRAPER DESIGN; SOURCE: *MAGNETIC RECORDING: THE FIRST 100 YEARS*, EDITED BY E. D. DANIEL ET AL. IEEE PRESS, 1999

The technology of computer hard drives is fast approaching a physical barrier imposed by the superparamagnetic effect. Overcoming it will require tricky innovations

by Jon William Toigo

Many corporations find that the volume of data generated by their computers doubles every year. Gargantuan databases containing more than a terabyte—that is, one trillion bytes—are becoming the norm as companies begin to keep more and more of their data on-line, stored on hard-disk drives, where the information can be accessed readily. The benefits of doing so are numerous: with the right software tools to retrieve and analyze the data, companies can quickly identify market trends, provide better customer service, hone manufacturing processes, and so on. Meanwhile individual consumers are using modestly priced PCs to handle a data glut of their own, storing countless e-mails, household accounting spreadsheets, digitized photographs, and software games.

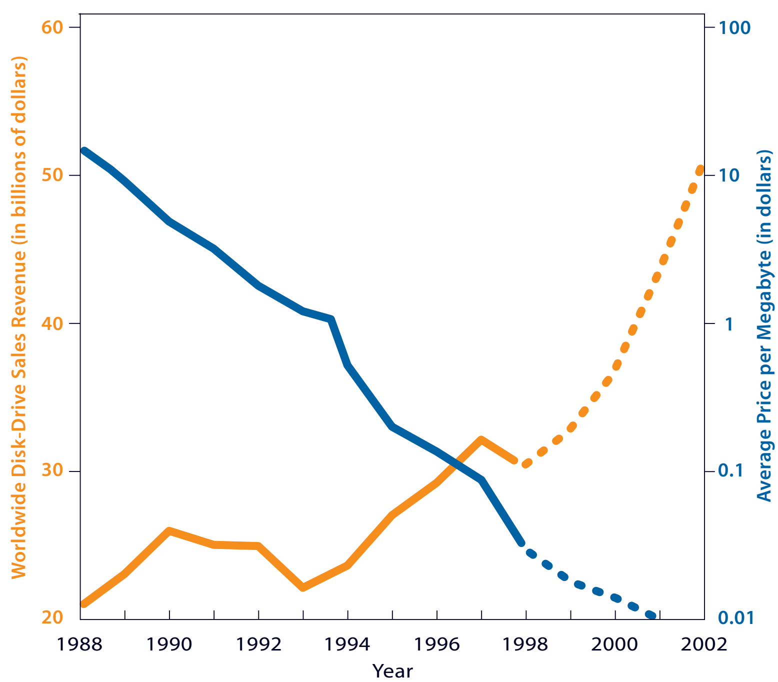
All this has been enabled by the availability of inexpensive, high-capacity magnetic hard-disk drives. Improvement in the technology has been nothing short of legendary: the capacity of hard-disk drives grew about 25 to 30 percent each year through the 1980s and accelerated to an average of 60 percent in the 1990s. By the end of last year the annual increase had reached 130 percent. Today disk capacities are doubling every nine months, fast outpacing advances in computer chips, which obey Moore's Law (doubling every 18 months).

At the same time, the cost of hard-disk drives has plummeted. Disk/Trend, a Mountain View, Calif.–based market research firm that tracks the industry, reports that the average price per megabyte for hard-disk drives plunged from \$11.54 in 1988 to \$0.04 in 1998, and the estimate for last year is \$0.02. James N. Porter, president of Disk/Trend, predicts that by 2002 the price will have fallen to \$0.003 per megabyte.

Not surprisingly, this remarkable combination of rising capacity and declining price has resulted in a thriving market. The industry shipped 145 million hard-disk drives in 1998 and nearly 170 million last year. That number is expected to surge to about 250 million in 2002, representing revenues of \$50 billion, according to Disk/Trend projections.

But whether the industry can maintain these fantastic economics is highly questionable. In the coming years the technology could reach a limit imposed by the superparamagnetic effect, or SPE. Simply described, SPE is a physical phenomenon that occurs in data storage when the energy that holds the magnetic spin in the atoms making up a bit (either a 0 or 1) becomes comparable to the ambient thermal energy. When that happens, bits become subject to random "flipping" between 0's and 1's, corrupting the information they represent.

In the quest to deliver hard disks with



SALES OF HARD-DISK DRIVES have soared as costs per megabyte have plummeted. Sales revenues are expected to grow to \$50 billion in 2002.

BRYAN CHRISTIE; SOURCE: DISK/TREND

ever increasing capacities, IBM, Seagate Technology, Quantum Corporation and other manufacturers have continually crammed smaller and smaller bits together, which has made the data more susceptible to SPE. With the current pace of miniaturization, some experts believe the industry could hit the SPE wall as early as 2005. But researchers have been busy devising various strategies for avoiding the SPE barrier. Implementing them in a marketplace characterized by fierce competition, frequent price wars and cost-conscious consumers will take a Herculean feat of engineering.

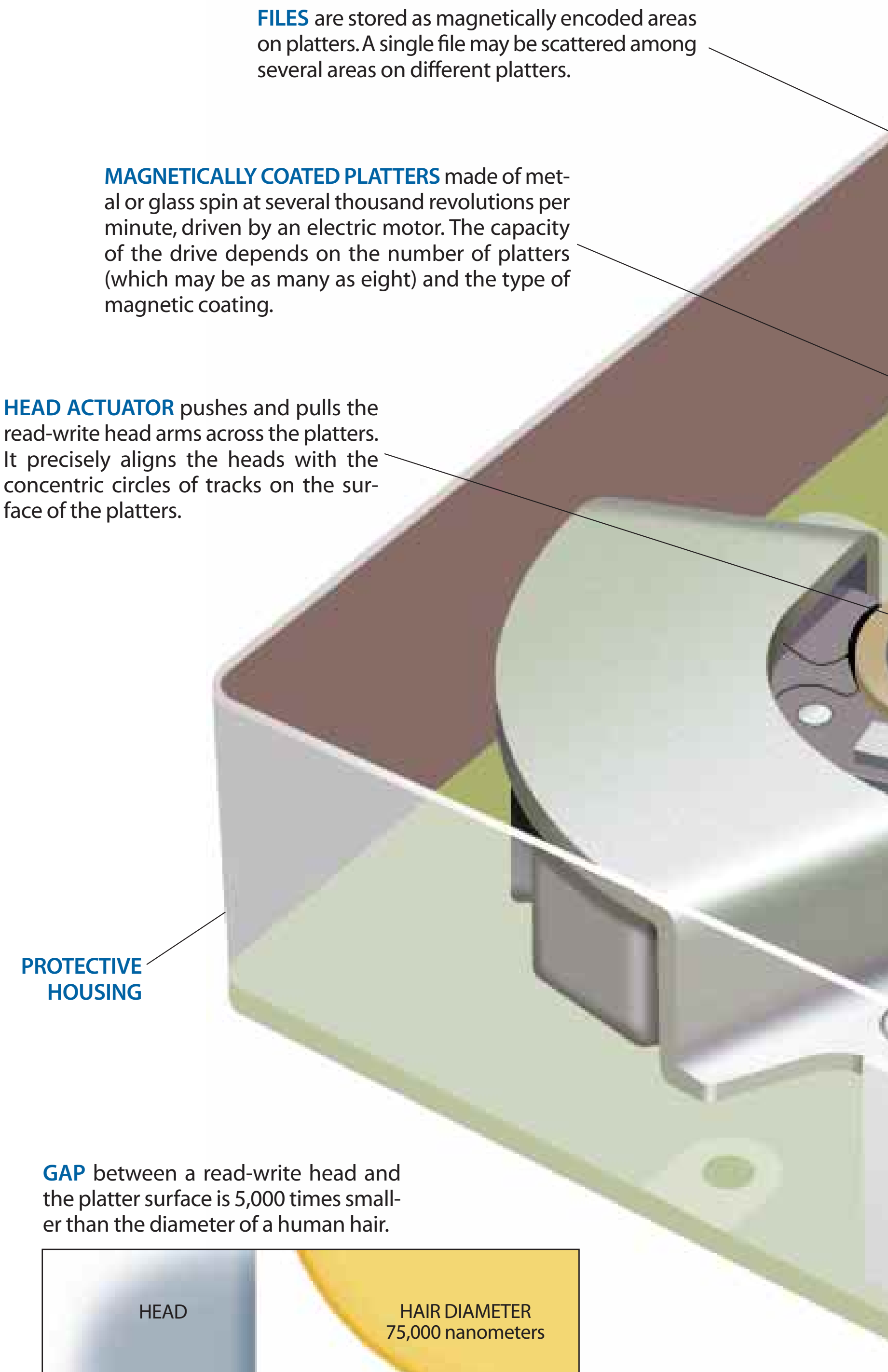
Magnetic Marvels

The hard-disk drive is a wonder of modern technology, consisting of a stack of disk platters, each one an aluminum alloy or glass substrate coated with a magnetic material and protective layers. Read-write heads, typically located on both sides of each platter, record and retrieve data from circumferential tracks on the magnetic medium. Servomechanical actuator arms position the heads precisely above the tracks, and a hydrodynamic air bearing is used to "fly" the heads above the surface at heights measured in fractions of microinches. A spindle motor rotates the stack at speeds of between 3,600 and 10,000 revolutions per minute.

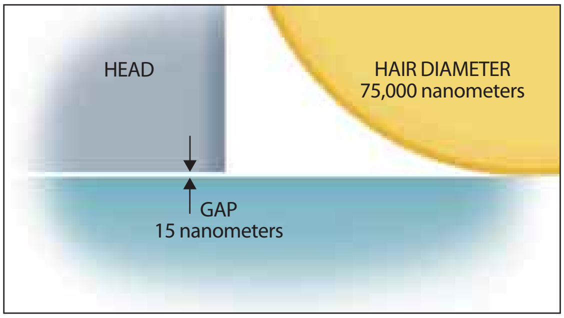
This basic design traces its origins to the first hard-disk drive—the Random Access Method of Accounting and Control (RAMAC)—which IBM introduced in 1956. The RAMAC drive stored data on 50 aluminum platters, each of which was 24 inches in diameter and coated on both sides with magnetic iron oxide. (The coating was derived from the primer used to paint San Francisco's Golden Gate Bridge.) Capable of storing up to five million characters, RAMAC weighed nearly a ton and occupied the same floor space as two modern refrigerators.

In the more than four decades since then, various innovations have led to dramatic increases in storage capacity and equally amazing decreases in the physical dimensions of the drives themselves. Indeed, storage capacity has jumped multiple orders of magnitude during that time, with the result that some of today's desktop PCs have disk drives containing more than 70 gigabytes. Tom H. Porter, chief technology officer at California-based Seagate Technology's Minneapolis office, explains

HOW A HARD-DISK DRIVE WORKS



GAP between a read-write head and the platter surface is 5,000 times smaller than the diameter of a human hair.



READ-WRITE HEADS, attached to the ends of moving arms, slide across both the top and bottom surfaces of the spinning platters. The heads write the data to the platters by aligning the magnetic fields of particles on the platters' surfaces; they read data by detecting the polarities of particles that have already been aligned.

PRINTED CIRCUIT BOARD receives commands from the drive's controller. The controller is managed by the operating system and the basic input-output system, low-level software that links the operating system to the hardware. The circuit board translates the commands into voltage fluctuations, which force the head actuator to move the read-write heads across the surfaces of the platters. The board also controls the spindle that turns the platters at a constant speed and tells the drive heads when to read from and when to write to the disk.

GEORGE RETSECK; SOURCE: *HOW COMPUTERS WORK*, BY RON WHITE. FOURTH EDITION. QUE CORPORATION, 1998 that the industry has achieved these improvements largely through straightforward miniaturization. "Smaller heads, thinner disks, smaller fly heights [the distance between head and platter]: everything has been about scaling," he notes.

Head Improvements

Many of the past improvements in disk-drive capacity have been a result of advances in the read-write head, which records data by altering the magnetic polarities of tiny areas, called domains (each domain representing one bit), in the storage medium. To retrieve that information, the head is positioned so that the magnetic states of the domains produce an electrical signal that can be interpreted as a string of 0's and 1's.

Early products used heads made of ferrite, but beginning in 1979 silicon chip–building technology enabled the precise fabrication of thin-film heads. This new type of head was able to read and write bits in smaller domains. In the early 1990s thin-film heads themselves were displaced with the introduction of a revolutionary technology from IBM. The innovation, based on the magnetoresistive effect (first observed by Lord Kelvin in 1857), led to a major breakthrough in storage density.

Rather than reading the varying magnetic field in a disk directly, a magnetoresistive head looks for minute changes in the electrical resistance of the overlying read element, which is influenced by that magnetic field. The greater sensitivity that results allows data-storing domains to be shrunk further. Although manufacturers continued to sell thin-film heads through 1996, magnetoresistive drives have come to dominate the market.

In 1997 IBM introduced another innovation—the giant magnetoresistive (GMR) head—in which magnetic and nonmagnetic materials are layered in the read head, roughly doubling or tripling its sensitivity. Layering materials with different quantum-mechanical properties enables developers to engineer a specific head with desired GMR capabilities. Currie Munce, director of storage systems and technology at the IBM Almaden Research Center in San Jose, Calif., says developments with this technology will enable disk drives to store data at a density exceeding 100 gigabits per square inch of platter space.

Interestingly, as recently as 1998 some experts thought that the SPE limit was 30 gigabits per square inch. Today no one seems to know for sure what the exact barrier is, but IBM's achievement has made some assert that the "density demon" lives somewhere past 150 gigabits per square inch.

A Bit about Bit Size

Of course, innovations in read-write heads would be meaningless if the disk platters could not store information more densely. To fit more data onto a disk, says Pat McGarrah, a director of strategic and technical marketing at Quantum Corporation in Milpitas, Calif., many companies are looking for media that will support shorter bits.

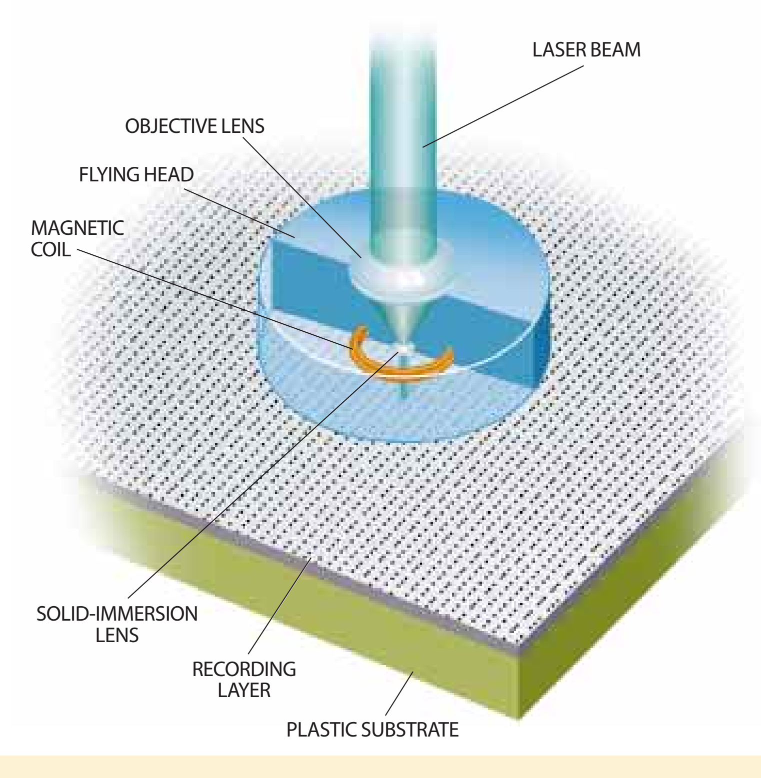
The problem, though, is SPE: as one shrinks the size of grains or crystals of magnetic material to make smaller bits, the grains can lose the ability to hold a magnetic field at a given temperature. "It really comes down to the thermal stability of the media," Munce explains. "You can make heads more sensitive, but you ultimately need to consider the properties of the media material, such as the coercivity, or magnetic stability, and how few grains you can use to obtain the desired resistance to thermal erasure."

ADDING OPTICAL TO MAGNETIC

One strategy for extending the life span of the workhorse magnetic-disk drive is to supplement it with optical technology. Such a hybrid approach could push storage densities to well beyond the current range of 10 to 30 gigabits per square inch. In fact, TeraStor in San Jose, Calif., claims that capacities could eventually top 200 gigabits per square inch, surpassing the anticipated limit imposed by the superparamagnetic effect [*see main article*].

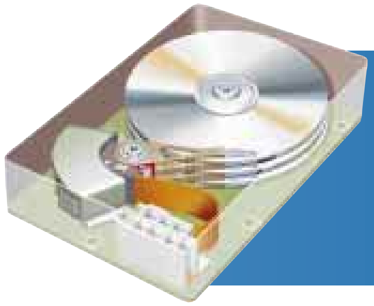
The TeraStor disk drive is essentially a variation of magneto-optical technology, in which a laser heats a small spot on the disk so that information can then be written there magnetically. A crucial difference, however, is that TeraStor uses a solid-immersion lens, or SIL, which is a special type of truncated spherical lens.

Invented at Stanford University, SILs rely on the concept of liquid-immersion microscopy, in which both the lens and object being studied are placed in a liquid, typically oil, that greatly boosts the magnification. But SILs apply the technique in reverse



LASER BEAM heats a tiny spot on a disk, which permits the flying head to alter the magnetic properties of the spot so that it stores a binary 1 or 0. Two lenses focus the beam to an extremely fine point, enabling the bits to be written onto the disk at very high density. An objective lens concentrates the beam on a solid-immersion lens—the cornerstone of the system—which in turn focuses the light to a spot smaller than a micron across.

GEORGE RETSECK



By 2002 the average price per megabyte for hard-disk drives will have fallen to $0.003, predicts James Porter, Disk/Trend

Traditionally, Munce says, a minimum of about 500 to 1,000 grains of magnetic material was required to store a bit. (In March, however, IBM scientists announced a process for self-assembling magnetic particles into bits that could provide areal densities as high as 150 gigabits per square inch.) Currently researchers are actively looking for improved materials that can hold a detectable magnetic charge and resist SPE with fewer grains. Also, the industry has been developing better manufacturing processes to decrease the impurities in the storage medium and thereby enable smaller bits.

In lieu of improvements of this type, the limit of bits per inch will remain in the range of between 500,000 and 650,000, according to Karl A. Belser, a storage technologist for Seagate Technology's research division. But this parameter, which is for data stored in a particular track on a platter, is only one determinant of areal density, which is the number of bits per square inch.

Tracking the Tracks

Storage capacity also depends on the narrowness of the tracks, and so far manufacturers have been able to cram up to 20,000 tracks per inch. This number is limited by various factors, such as the ability of the recording head to resolve the different tracks and the accuracy of its position-sensing system. Squeezing in additional tracks will require significant improvements in several areas, including the design of the head and the actuator that controls that head. To achieve an overall density of 100 gigabits per square inch, the industry must somehow figure out a way to fit about 150,000 tracks or more per inch.

With the existing technology, tracks must be separated by gaps of 90 to 100 nanometers, according to Belser. "Most write heads look like a horseshoe that extends across the width of a track," he explains. "They write in a longitudinal direction [that is, along the circular track], but they also generate fringe fields that extend radially." If the tracks are spaced too closely, this effect can cause information on adjacent tracks to be overwritten and lost.

One solution is to fabricate the recording head more precisely to smaller dimensions. "You can use a focused ion beam to trim the write head and to narrow the width of the track that a writer writes," Belser says. But the read head, which is a complex sandwich of elements, poses a harder manufacturing problem. Furthermore, for 150,000 tracks or more per inch to be squeezed in, the tracks will have to be less than about 170 nanometers wide. Such mi-

GEORGE RETSECK

to focus a laser beam on a spot with dimensions of less than a micron [*see illustration at left*]. The TeraStor technology is called "near field" because the read-write head must be extremely close to the storage medium (the separation is less than the wavelength of the laser beam).

The recording medium consists of a layer of magnetic material similar to that used in magneto-optical systems. But rather than being a magnetic layer encased in plastic, the recording layer is placed on top of a plastic substrate, which reduces the production cost and permits data to be written directly onto the recording surface.

As on a conventional magnetic disk, data bits (domains) are laid down one after the other. But the near-field bits are written standing up, or perpendicular to the plane of the disk, and not horizontally along the disk surface. "The magnetic fields of the domains poke out of the media vertically, rather than being laid out longitudinally," explains Gordon R. Knight, chief technology officer for TeraStor. "This configuration means that the magnetic fields of the bits support each other, unlike the fields of horizontally recorded bits, and are not subject to the superparamagnetic effect."

Furthermore, the ultrasmall domains are written in overlapping sequences, creating a series of crescent-shaped bits. This recording method effectively doubles the number of bits that can be written linearly in a track, thus enabling the TeraStor technology to achieve a higher storage capacity. Information is read by exploiting the so-called Kerr effect. A beam of light is bounced off a domain on the disk. Depending on whether the crystals in the domain have been magnetized to represent a 0 or a 1, they will polarize the reflected light in different directions.

The TeraStor technology has been under development for more than five years, and Knight acknowledges that the delivery of products has been delayed several times as the company works out various technical kinks. TeraStor did, however, demonstrate several prototypes at an industry trade show late last year, and the company has already lined up various manufacturing partners, including Maxell and Toso for the storage medium, Olympus for the optical components, Texas Instruments for the supporting electronic chips, and Mitsumi for the drive assembly. Industry heavyweight Quantum Corporation in Milpitas, Calif., which has a financial stake in TeraStor, has provided additional technology and access to its research lab.

If all goes well, TeraStor will be shipping products by the end of 2000. But the drives will contain just 20 gigabytes of storage on a removable CD-size medium. (Current hard drives already boast more than 70 gigabytes.) Knight asserts that the initial products may replace tape and optical storage products in applications in which access speed is important, such as digital video editing. He contends that the technology will ultimately make possible disk drives with much higher capacity—greater than 300 gigabytes—which may enable it to compete more directly with magnetic-disk drives. *—J.W.T.*

croscopically narrow tracks will be difficult for the heads to follow, and thus each head will need a secondary actuator for precise positioning. (In current products, just one actuator controls the entire assembly of heads.)

Last, smaller bits in thinner tracks will generate weaker signals. To separate those signals from background noise, researchers need to develop new algorithms that can retrieve the information accurately. Today's software requires a signal-to-noise ratio of at least 20 decibels. Says Belser, "The industry is at least six decibels short of being able to work with the signal-to-noise ratio that would apply when dealing with the bit sizes entailed in disks with areal densities of 100 to 150 gigabits per square inch."

Nevertheless, such problems are well understood, many industry experts concur. In fact, Munce asserts that the improvements in materials, fabrication techniques and signal processing already being studied at IBM and elsewhere will, over the next few years, enable the manufacture of disk drives with areal densities in the range of 100 to 150 gigabits per square inch.

USING "HARD" MATERIALS

An obvious way to cram more information onto a disk is to shrink the size of the data bits by using fewer or smaller grains of a magnetic material for each bit. The problem, though, is that the tiny bits begin to interfere with one another (think of what happens when two bar magnets are brought close to each other). To prevent such corruption of data, which is caused by the superparamagnetic effect, researchers have been investigating the use of certain rare-earth and transition elements that are very magnetically stable. In the industry lingo, such metals have high coercivity and are called "hard."

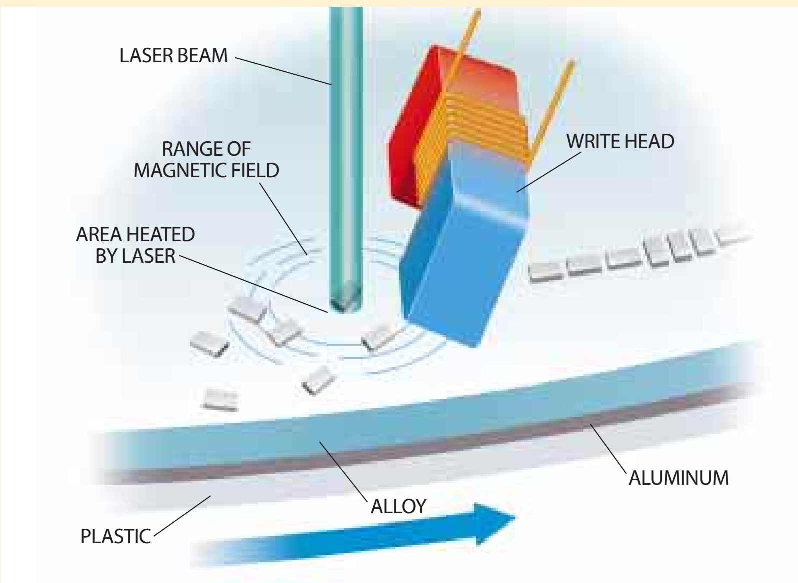
But a hard material is difficult to write on, so it may first be "softened" by being heated with a laser. This process lowers the coercivity of the grains so that data can then be written to them. As the material cools, it hardens, protecting the stored information from the vicissitudes of superparamagnetism. The concept sounds simple enough, but it has been difficult to implement: the laser beam must avoid accidentally heating adjacent bits that contain previously stored data.

To that end, Seagate Technology, headquartered in Scotts Valley, Calif., is using a disk that has grooves between the circular tracks of bits (much as a vinyl record does). The grooves block the laser heat from flowing to neighboring tracks. To record information in those narrow tracks, Seagate has been developing a new type of write head that is controlled by a special actuator. Details of these components are being kept under wraps.

The read head also presents certain difficulties. Because even the current experimental devices are three tracks wide instead of one, they have the potential to pick up unwanted noise during the reading process, according to Karl A. Belser, a storage technologist with Seagate. Even if a narrower head were developed, the device would need to be positioned precisely to follow the extremely thin tracks. Solutions include the use of a laser-positioning system, but that would add complexity—and cost—to the overall drive.

An alternative is to make the medium easier to read. This can be done by using a two-layer medium with a permanent storage layer positioned below a readout layer. To read data on the medium, the readout layer would be magnetically erased, and then the appropriate track of the storage layer would be heated with a laser to bring its data to the readout layer through a magnetic coupling process similar to current magneto-optical disk processes. Once the track had been written to the readout layer, its bits could be read in isolation from other tracks. Without the noise of adjacent tracks, even a wide head could read the information in the readout track.

If such a system were workable, the technology could store 1,000 gigabits per square inch, according to Seagate. In contrast, conventional wisdom holds that the superparamagnetic effect limits the storage density of traditional disk drives to a range of 100 to 150 gigabits per square inch. But even Seagate admits that it is at least four years from commercializing its thermally assisted magnetic drives. *—J.W.T.*



GEORGE RETSECK; SOURCE: *HOW COMPUTERS WORK*, BY RON WHITE. FOURTH EDITION. QUE CORPORATION, 1998

MAGNETO-OPTICAL DRIVE heats a spot with a laser, loosening magnetic crystals so that they can be reoriented with a magnetic field. This basic concept has been difficult to miniaturize because the laser must avoid accidentally heating—and thus possibly destroying—previously stored data. One solution is to manufacture a disk with grooves between concentric tracks of data to block heat from flowing between the tracks. To read the information, Seagate Technology is considering the use of a two-tier system in which the data are stored in tracks on a lower level. When the data are to be read out, a laser heats a section of a track in the lower layer. The heating induces magnetic coupling that transfers the data to the upper level of the disk, where they can be read out in the absence of interfering fields from adjacent tracks.

The introduction of thin-film heads took nearly 10 years. The transition from that to magnetoresistive technology required six more years because of various technical demands, including separate read and write elements for the head, a manufacturing technique called sputter deposition and different servo controls. "Going from thin-film inductive heads to MR heads entailed a number of new processes," Munce remarks. "Delays were bound to happen."

But the switch to giant magnetoresistive drives is occurring much faster, taking just between 12 and 18 months. In fact, IBM and Toshiba began shipping such products before the rest of the industry had fully converted to magnetoresistive heads.

The quick transition was possible because giant magnetoresistive heads have required relatively few changes in the surrounding disk-drive components. According to Munce, the progression to drive capacities of 100 gigabits per square inch will likewise be evolutionary, not revolutionary, requiring only incremental steps.

The Issue of Speed

But storage capacity is not the only issue. Indeed, the rate with which data can be accessed is becoming an important factor that may also determine the useful life span of magnetic disk-drive technology. Although the capacity of hard-disk drives is surging by 130 percent annually, access rates are increasing by a comparatively tame 40 percent.

To improve on this, manufacturers have been working to increase the rotational speed of drives. But as a disk spins more quickly, air turbulence and vibration can cause misregistration of the tracks—a problem that could be corrected by the addition of a secondary actuator for every head. Other possible enhancements include the use of fluid bearings in the motor to replace steel and ceramic ball bearings, which wear and emit noticeably audible noise when platters spin at speeds greater than 10,000 revolutions per minute.

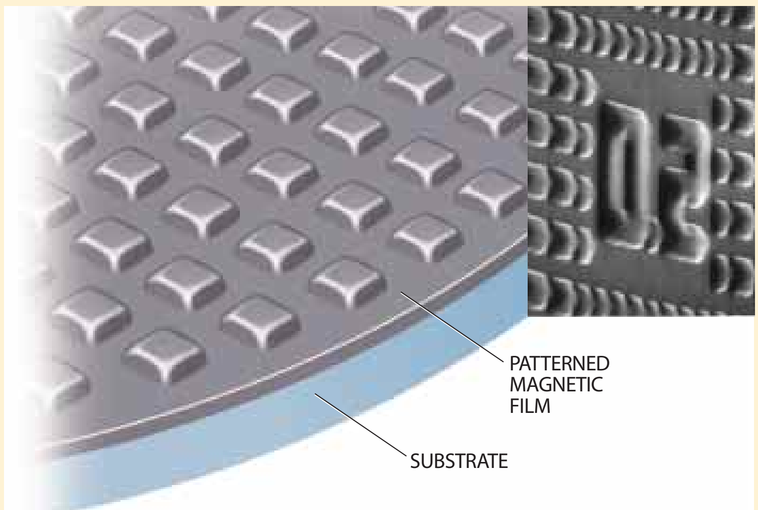
Many industry onlookers foresee a possible bifurcation in the marketplace, with some disk drives optimized for capacity and others for speed. The former might be used for mass storage, such as for backing up a company's historical files. The latter would be necessary for applications such as customer service, in

PATTERNS OF BITS

Magnetic hard drives can store data at incredible densities—more than 10 gigabits per square inch of disk space. But as manufacturers cram information ever more tightly, the tiny bits begin to interfere with one another—the superparamagnetic effect [*see main article*]. One simple solution is to segregate the individual bits by erecting barriers between them. This approach, called patterned media, has been an ongoing area of research at most laboratories doing advanced work in storage technology.

One type of patterned media consists of "mesas" and "valleys" fabricated on the surface of a disk platter, with each mesa storing an individual bit. According to proponents of this approach, one bit of data (either a 0 or 1) could theoretically be stored in a single grain, or crystal, of a magnetic material. In contrast, conventional hard-disk technology requires a minimum of about 500 to 1,000 grains for each bit. Thus, with a grain size of seven to eight nanometers in diameter, this type of storage could achieve a density of more than 10,000 gigabits (or 10 terabits) per square inch.

To fabricate the mesas and valleys, companies have been investigating photolithographic processes used by the chip industry. "Electron beams or lasers would be needed to etch the pattern [onto the storage medium].



GEORGE RETSECK; IBM (*micrograph*)

"MESAS AND VALLEYS" of a future magnetic disk could help manufacturers avoid the superparamagnetic effect, in which closely packed bits in the magnetic media interfere with one another. In this patterned approach, the problem is circumvented by segregating each bit in its own mesa. The difficulty is in making the mesas small enough: they would have to be around eight nanometers across or smaller in order to achieve the kind of densities that developers are seeking. IBM has been able to build such structures with feature sizes as small as 0.1 and 0.2 micron (*inset*), or 100 and 200 nanometers.

Mesas would then need to be grown on a substrate layer, one bit in diameter," explains Gordon R. Knight, chief technology officer at TeraStor. But this technique needs much refinement. One estimate is that the current lithographic processes can at best make mesas that are about 80 nanometers in diameter—an order of magnitude too large for what is needed.

Even if the industry could obtain sufficiently tiny mesas and valleys, it would still need a revolutionary new type of head to read the data, says Currie Munce, director of storage systems and technology at the IBM Almaden Research Center in San Jose, Calif. According to Munce, various signal-to-noise issues would necessitate a radical departure from current magnetic-disk systems. Consequently, most experts agree that patterned-media technology will take years to become practical. —*J.W.T.*

which the fast retrieval of data is crucial.

In the past, customers typically preferred a bigger drive at the lowest possible cost, even if the product had slower performance. "In our hypercompetitive industry, drives with 30 to 40 percent higher performance sell for only about a 20 percent higher price," Munce notes.

But new applications are demanding faster drives. With electronic commerce over the World Wide Web, for example, companies need to store and retrieve customer data on the fly. In addition, businesses are deploying an increasing number of dedicated file servers for information that needs to be shared and accessed quickly by a number of employees.

The capacity-versus-performance debate could become acute as the industry considers various ways to avoid the SPE barrier. Experts agree that moving beyond areal densities of 150 gigabits per square inch will require a significant

ON THE HORIZON: HOLOGRAPHIC STORAGE

For nearly four decades, holographic memory has been the great white whale of technology research. Despite enormous expenditures, a complete, general-purpose system that could be sold commercially continues to elude industrial and academic researchers. Nevertheless, they continue to pursue the technology aggressively because of its staggering promise.

Theoretical projections suggest that it will eventually be possible to use holographic techniques to store trillions of bytes—an amount of information corresponding to the contents of millions of books—in a piece of crystalline material the size of a sugar cube or a standard CD platter. Moreover, holographic technologies permit retrieval of stored data at speeds not possible with magnetic methods. In short, no other storage technology under development can match holography's capacity and speed potential.

These facts have attracted name-brand players, including IBM, Rockwell, Lucent Technologies and Bayer Corporation. Working both independently and in some cases as part of research consortia organized and co-funded by the U.S. Defense Advanced Research Projects Agency (DARPA), the companies are striving to produce a practical commercial holographic storage system within a decade.

Since the mid-1990s, DARPA has contributed to two groups working on holographic memory technologies: the Holographic Data Storage System (HDSS) consortium and the PhotoRefractive Information Storage Materials (PRISM) consortium. Both bring together companies and academic researchers at such institutions as the California Institute of Technology, Stanford University, the University of Arizona and Carnegie Mellon University. Formed in 1995, HDSS was given a five-year mission to develop a practical holographic memory system, whereas PRISM, formed in 1994, was commissioned to produce advanced storage media for use in holographic memories by the end of this year.

With deadlines for the two projects looming, insiders report some significant recent advances. For example, late last year at Stanford, HDSS consortium members demonstrated a holographic memory from which data could be read out at a rate of a billion bits per second. At about the same time, an HDSS demonstration at Rockwell in Thousand Oaks, Calif., showed how a randomly chosen data element could be accessed in 100 microseconds or less, a figure the developers expect to reduce to tens of microseconds. That figure is superior by several orders of magnitude to the retrieval speed of magnetic-disk drives, which require milliseconds to access a randomly selected item of stored data. Such a fast access time is possible because the laser beams that are central to holographic technologies can be moved rapidly without inertia, unlike the actuators in a conventional disk drive.

Although the 1999 demonstrations differed significantly in terms of storage media and reading techniques, certain fundamental aspects underlie both demonstration systems. An important one is the storage and retrieval of entire pages of data at one time. These pages might contain thousands or even millions of bits.

Each of these pages of data is stored in the form of an optical-interference pattern within a photosensitive crystal or polymer material. The pages are written into the material, one after another, using two laser beams. One of them, known as the object or signal beam, is imprinted with the page of data to be stored when it shines through a liquid-crystal-like screen known as a spatial-light modulator. The screen displays the page of data as a pattern of clear and opaque squares that resembles a crossword puzzle.

A hologram of that page is created when the object beam meets the second beam, known as the reference beam, and the two beams interfere with each other inside the photosensitive recording material. Depending on what the recording material is made of, the optical-interference pattern is imprinted as the result of physical or chemical changes in the material. The pattern is imprinted throughout the material as variations in the refractive index, the light absorption properties or the thickness of the photosensitive material.

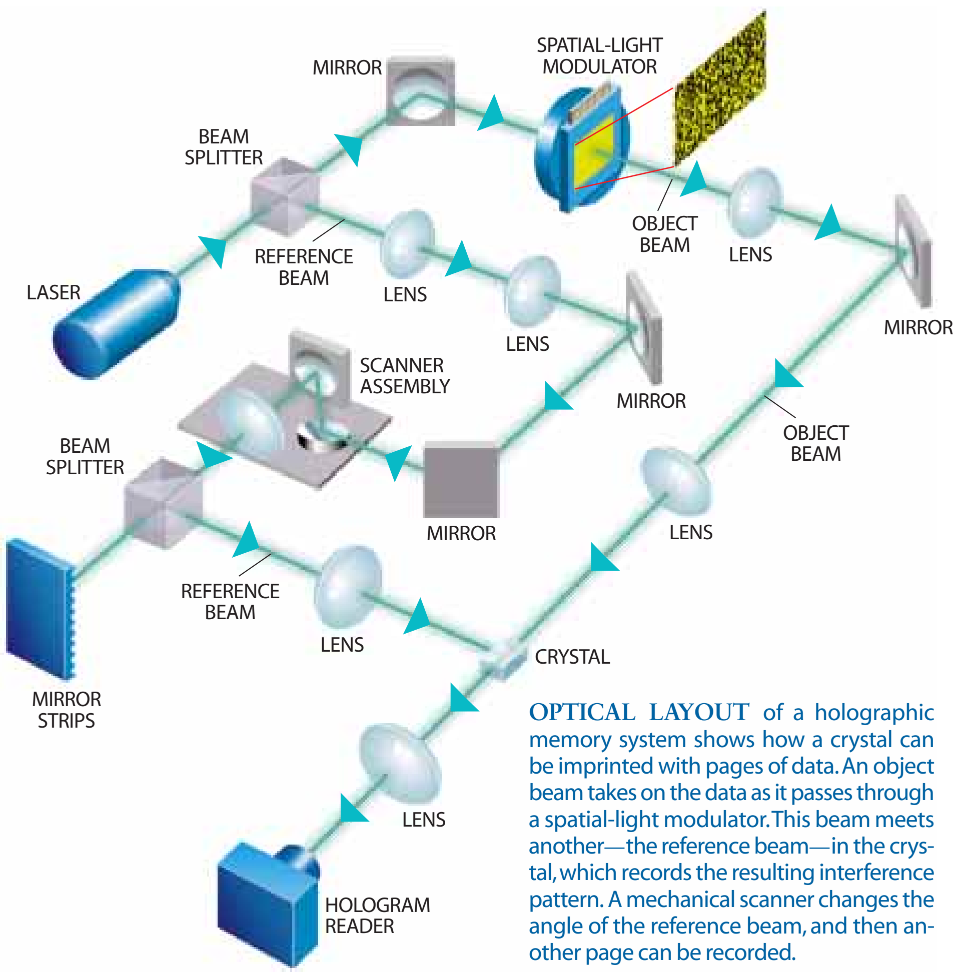
When this stored interference pattern is illuminated with either of the two original beams, it diffracts the light so as to reconstruct the other beam used to produce the pattern originally. Thus, illuminating the material with the reference beam re-creates the object beam, with its imprinted page of data. It is then a relatively simple matter to detect the data pattern with a solid-state camera chip, similar to those used in modern digital video cameras. The data from the chip are interpreted and forwarded to the computer as a stream of digital information.

Researchers put many different interference patterns, each corresponding to a different page of data, in the same material. They separate the pages either by varying the angle between the object and reference beams or by changing the laser wavelength.

Rockwell, which is interested in developing holographic memories for applications in defense and aerospace, optimized its demonstration system for fast data access, rather than for large storage capacities. Thus, its system utilized a unique, very high speed acousto-optical-positioning system to steer its laser through a lithium niobate crystal. By contrast, the demonstration at Stanford, including technologies contributed by IBM, Bayer and others, featured a high-capacity polymer disk medium about the size of a CD platter to store larger amounts of data. In addition, the Stanford system emphasized the use of components and materials that could be readily integrated into future commercial holographic storage products.

According to Hans Coufal, who manages IBM's participation in both HDSS and PRISM, the company's strategy is to make use of mass-produced components wherever possible. The lasers, Coufal points out, are similar to those that are found in CD players, departure from conventional magnetic hard disks. Some of the alternatives boast impressive storage capabilities but mediocre speeds, which would limit their use for certain applications. At present, the main strategies include:

- Change the orientation of the bits on the disk from longitudinal (circumferential) to perpendicular, or vertical, to cram more of them together and to prevent them from flipping [*see box on page 64*].
- Use magnetic materials, such as alloys of iron/platinum or cobalt/samarium, that are more resistant to SPE. If the magnetic "hardness" of the material is a problem for recording data, heat the medium first to "soften" it magnetically before writing on it [*see box on page 66*].
- Imprint a pattern lithographically onto the storage medium to build microscopic barriers between individual bits [*see box on page 67*].
- Use a radically different storage material, such as holographic crystals [*see*



OPTICAL LAYOUT of a holographic memory system shows how a crystal can be imprinted with pages of data. An object beam takes on the data as it passes through a spatial-light modulator. This beam meets another—the reference beam—in the crystal, which records the resulting interference pattern. A mechanical scanner changes the angle of the reference beam, and then another page can be recorded.

um niobate and other inorganic substances and photorefractive, photochromic and photochemical polymers, which are in development at Bayer and elsewhere. He notes that independent work by Lucent and by Imation Corporation in Oakdale, Minn., is also yielding promising media prospects. No materials that IBM has tested so far, however, have yielded the mix of performance, capacity and price that would support a mainstream commercial storage system.

Both Munce and Coufal say that IBM's long-standing interest in holographic storage intensified in the late 1990s as the associative retrieval properties of the medium became better understood. Coufal notes that past applications for holographic storage targeted the permanent storage of vast libraries of text, audio and video data in a small space. With the growing commercial interest in data mining—essentially, sifting through extremely large warehouses of data to find relationships or patterns that might guide corporate decision making and business process refinements—holographic memory's associative retrieval capabilities seem increasingly attractive.

After data are stored to a holographic medium, a single desired data page can be projected that will reconstruct all reference beams for similarly patterned data stored in the media. The intensity of each reference beam indicates the degree to which the corresponding stored data pattern matches the desired data page.

"Today we search for data on a disk by its sector address, not by the content of the data," Coufal explains. "We go to an address and bring information in and compare it with other patterns. With holographic storage, you could compare data optically without ever having to retrieve it. When searching large databases, you would be immediately directed to the best matches."

While the quest for the ideal storage medium continues, practical applications such as data mining increase the desirability of holographic memories. And with even one business opportunity clearly defined, the future of holographic storage systems is bright indeed.

—*J.W.T.*

and the spatial-light modulators resemble ordinary liquid-crystal displays.

Nevertheless, significant work remains before holographic memory can go commercial, Coufal says. He reports that the image of the data page on the camera chip must be as close to perfect as possible for holographic information storage and retrieval to work. Meeting the exacting requirements for aligning lasers, detectors and spatial-light modulators in a low-cost system presents a significant challenge.

Finding the right storage material is also a persistent challenge, according to Currie Munce, director of storage systems and technology at the IBM Almaden Research Center. IBM has worked with a variety of materials, including crystal cubes made of lithi-

A DECADE AWAY: ATOMIC RESOLUTION STORAGE

Chuck Morehouse, director of Hewlett-Packard's Information Storage Technology Lab in Palo Alto, Calif., is quick to point out that atomic resolution storage (ARS) will probably never completely replace rotational magnetic storage. Existing hard-disk drives and drive arrays play well in desktops and data centers where device size is not a major issue. But what about the requirements for mass storage on a wristwatch or in a spacecraft, where form factor, mass and power consumption are overriding criteria?

The ARS program at Hewlett-Packard (HP) aims to provide a thumbnail-size device with storage densities greater than one terabit (1,000 gigabits) per square inch. The technology builds on advances in atomic probe microscopy, in which a probe tip as small as a single atom scans the surface of a material to produce images accurate within a few nanometers. Probe storage technology would employ an array of atom-size probe tips to read and write data to spots on the storage medium. A micromover would position the medium relative to the tips.

IBM and other companies are actively developing such probe storage technology, and Morehouse reports that the U.S. Department of Defense has a stake in the work. For example, the Defense Advanced Research Projects Agency (DARPA) is footing the bill for three HP researchers who are working on bringing a device from the test lab to the marketplace.

According to Morehouse, they face four primary challenges. First is the storage medium. The HP group has chosen one consisting of a material with two distinct physical states, or phases, that are stable at room temperature. One phase is amorphous, and the other is crystalline. Bits are set in this "phase-change medium" by heating data spots to change them from one phase to the other.

The second challenge is the probe tip, which must emit a well-directed beam of electrons when voltage is applied. A strong beam flowing from the tip to the medium heats a data spot as needed to write or erase a bit. A weak beam can be used to read data by detecting a spot's resistance or other phase-dependent electrical property. Optical reading techniques may also be possible. HP is looking at a "far-field" approach in which the tip is perhaps 1,000 nanometers from the medium, unlike most probe efforts in which the tip is in contact or almost in contact with the medium.

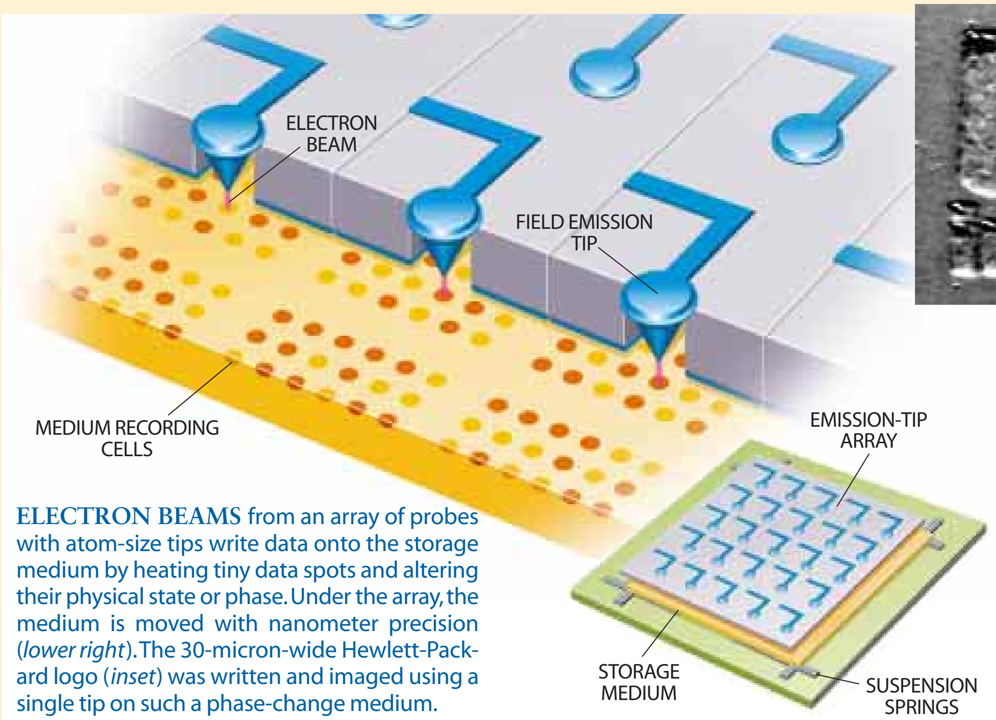
A third issue is the actuator or micromover that positions the media for reading and writing. HP is developing a micromotor with nanometer-level positioning capabilities.

The final step is packaging. Morehouse explains: "We need to get the ARS device together into a rugged package and develop the system electronics that will allow it to be integrated with other devices." An extra difficulty is that the working elements of the device will probably need to be in a vacuum or at least in a controlled atmosphere to reduce the scattering of electrons from the read-write beam and to reduce the flow of heat between data spots.

Morehouse sees the technology to create the ARS device becoming available within a decade but acknowledges that it may take considerably longer to bring the device to market. The magnetic-disk industry has a significant investment to protect, but he is confident that as applications demand the portability and performance that ARS offers, it will become a significant player in the storage market.

"My imagination for how it can be used is woefully inadequate," Morehouse says. Magnetic-disk drives are being scaled steadily downward in size—witness the example of IBM's Microdrive (340 megabytes in a one-inch form factor). Nevertheless, "ARS may be competitive for many applications," he notes. "One key advantage is low power consumption. When ARS is not being asked to perform an operation, it has no power consumption. Watchmakers may not want a Microdrive with a lot of batteries for a watch."

Morehouse says that the first ARS devices might have a one-gigabyte capacity but that capacities will increase over time: "The ultimate capacity will be determined by how small you can make a spot. Nobody knows the answer to that—100 atoms?" —

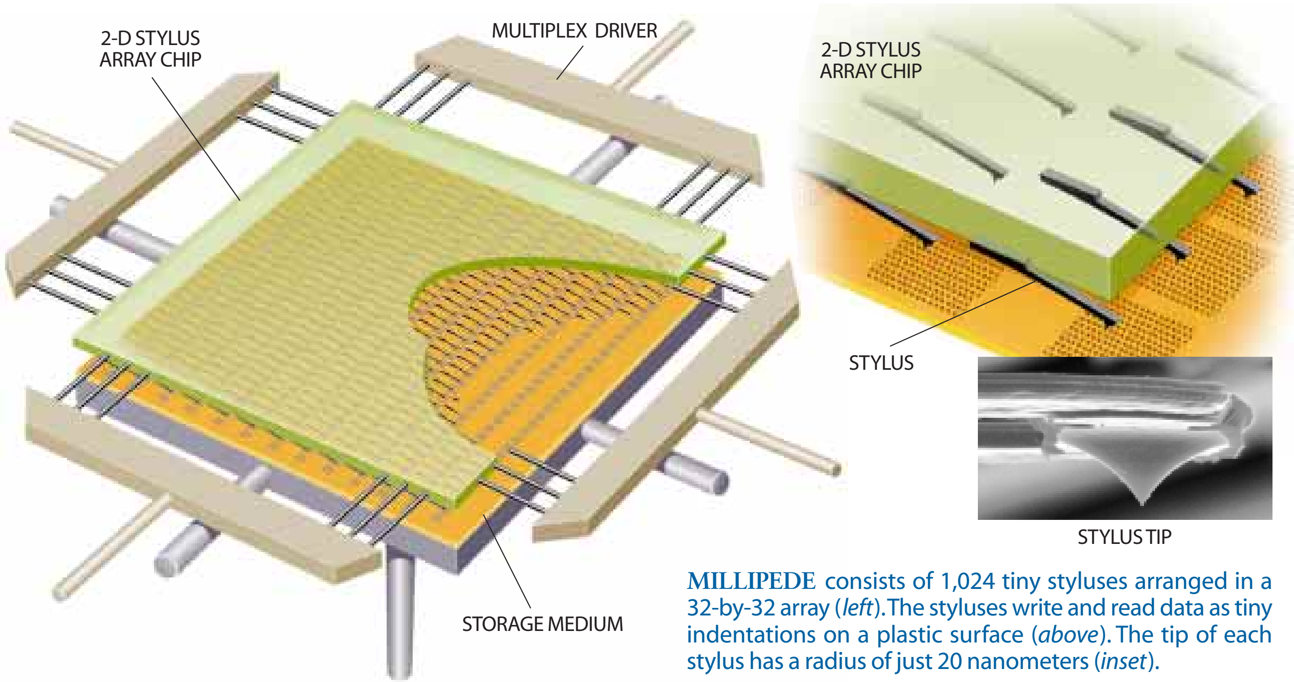


ELECTRON BEAMS from an array of probes with atom-size tips write data onto the storage medium by heating tiny data spots and altering their physical state or phase. Under the array, the medium is moved with nanometer precision (*lower right*). The 30-micron-wide Hewlett-Packard logo (*inset*) was written and imaged using a single tip on such a phase-change medium.

GEORGE RETSECK; HEWLETT-PACKARD (*micrograph*)

"PUNCH CARDS" OF THE FUTURE

Decades ago punch cards were a popular, if clunky, way to store information. Now their mechanical simplicity, shrunk to fantastically small dimensions, is back in vogue at IBM. The company's research group in Zurich has recently developed a prototype, dubbed Millipede, that can cram an amazing amount of information into a tiny space—500 gigabits per square inch—by storing the data as microscopic indentations on a flat polymer surface. In comparison, the workhorse magnetic-disk drive is currently limited to no more than 35 gigabits per square inch, even in the most advanced laboratory prototype.



MILLIPEDE consists of 1,024 tiny styluses arranged in a 32-by-32 array (*left*). The styluses write and read data as tiny indentations on a plastic surface (*above*). The tip of each stylus has a radius of just 20 nanometers (*inset*).

GEORGE RETSECK; IBM (*micrograph*)

"We've reinvented punch cards by using plastics," boasts Peter Vettiger, manager of the project for IBM.

To understand how Millipede works, think of another bygone technology: the phonograph stylus. In IBM's version the tip of the stylus is incredibly sharp (its radius is just 20 nanometers) and rests gently on a smooth, moving plastic surface. To create an indentation, an electric current zaps through the stylus, briefly heating the tip to 400 degrees Celsius, which melts the polymer slightly. A series of such current spikes thus produces a string of indentations, the dips and flats becoming the 0's and 1's of the digital world.

To read this information, the stylus tip is heated to a constant 350 degrees C (below the melting point of the plastic) as it moves across the polymer surface. When the stylus drops into an indentation, heat from the tip dissipates. The resulting temperature drop can be detected by a change in the electrical resistance of the stylus.

IBM has recently turned this basic technology, derived from atomic-force microscopy, into a working prototype. To increase the rate at which data are both written and read, the device consists of 1,024 styluses (hence the name "Millipede") in an area just three by three millimeters. Arranged in a 32-by-32 array, the styluses are made of silicon and operate simultaneously, making their indentations on a thin layer of plastic coated onto a silicon substrate.

One advantage of Millipede is its anticipated low manufacturing cost. IBM asserts that the arrays can be built economically with processes similar to those used to fabricate computer chips. "You could build hundreds of these arrays on the same wafer," Vettiger predicts.

For increased storage, he says, a future improvement might consist of a larger array (in an earlier incarnation, Millipede had just 25 styluses arranged five by five) or multiple arrays, or a combination of both. "We are completely open at this time. It's a very general concept," Vettiger contends. Another innovation might be the use of carbon nanotubes as stylus tips, which would make them even smaller.

Still, IBM must resolve several core issues before Millipede can become a practical product. One that the company is currently investigating is the long-term durability of the technology. Mechanical wear could dull the sharp tips of the styluses, making their indentations on the plastic surface larger. Eventually the markings might begin to overlap, turning pristine data into digital mush.

To be sure, much work remains before Millipede could even hope to supplant the venerable magnetic-disk drive. A greater opportunity might be in small consumer products. IBM is confident that it can develop a tiny device (10 by 10 by 5 millimeters or considerably smaller) that can store 10 gigabits, making the technology appropriate for cell phones, digital cameras and possibly watches. "This is where we'll concentrate our efforts over the next one to two years," Vettiger says. But he is the first to temper his growing excitement. "This is still an exploratory research project," he admits. "It's not as if tomorrow these products will come on the market." —*Alden M. Hayashi, staff writer*

New technologies will need to show a profit quickly and be able to compete economically with magnetic disks, warns Currie Munce, IBM Almaden Research Center

box on page 70], phase-change metals [*see box on page 72*], or plastic [*see box on page 73*].

Although several of these approaches have attracted large investments from the leading manufacturers, most remain in the very early stages of testing. Some of the concepts await research breakthroughs or key advances in supporting technologies before work can begin in earnest on prototypes.

Taking a Breather

Until then, hard-disk manufacturers will continue wringing additional improvements from conventional magnetic technology. "This industry seems to be following an S curve," Porter of Seagate observes. He explains that in the near term, manufacturers will still be riding the wave of advances made in the fields of photolithography and semiconductor-chip manufacturing, which enabled the economical fabrication of magnetoresistive and giant magnetoresistive heads. Consequently, the cost per storage bit has been dropping at a rate of 1.5 percent per week.

But experts agree that the industry will be hard-pressed to sustain that pace beyond the next few years. Gone will be the days when storage capacities grew by 130 percent annually. "Given the technological challenges," Munce says, "we will probably be back to a 60 percent annual growth rate within five years." Adds Porter, "Things are getting more difficult at a faster rate than they have historically. Perhaps a slowdown will give us time to evaluate options."

Interestingly, no one can be sure which of the alternative technologies will bear fruit. IBM itself is hedging its bets, investigating a number of approaches, including the use of patterned media, plastic media and holography. One thing is for certain, though. With the SPE specter looming and the industry confronting core design and materials issues, a window of opportunity might be opening.

But getting through that window will not be easy. "New technologies will need to show a profit quickly and be able to compete on a cost per gigabyte of storage with magnetic disks," Munce asserts. More likely, he adds, the new technologies might first need to carve out niches in the market. (Holographic crystals, for example, might be used for the permanent digitized storage of large libraries.) "The trend is definitely toward cost reduction," Munce points out, "which will make it very difficult for other technologies to get on the tracks."

Most observers agree that, regardless of the uncertainties of future data storage technologies, the Information Age will not come to a grinding halt as a result of the superparamagnetic effect. If delays are encountered in bringing higher-capacity products to market, the void is most likely to be filled in the interim by aggregating many drives into intelligent arrays that represent themselves as individual "virtual" drives to systems and to end users. This approach has already been seen in the case of Redundant Arrays of Inexpensive Disks (RAID) and Just a Bunch of Disks (JBOD) arrays that were deployed during the 1980s and 1990s to meet the storage capacity requirements of companies whose needs were not being satisfied by the single-drive capacities of the day.

Another approach that has garnered significant attention in the industry is to place drives and arrays into storage area networks (SANs) that can be scaled dynamically to meet growing storage appetites. The SAN approach further "virtualizes" storage and will eventually provide a "storage utility" that will automatically deliver to users applications with the size and kind of storage they require from a pool of interconnected storage devices.

These approaches to increasing storage capacity entail greater complexity and, by extension, greater management costs in comparison to single storage devices. But they do provide a means for addressing the needs of businesses and consumers for more elbow room for their data in the short term until new, higher-capacity technologies can be brought to market. Moreover, they will probably be facilitated by declining disk-drive prices, which will result from ongoing improvements in manufacturing processes. SA

The Author

JON WILLIAM TOIGO is an independent information technologies consultant. He is the author of eight books, including *The Holy Grail of Data Storage Management* (Prentice-Hall PTR, 2000), and has written numerous white papers and trade press articles on business automation and storage technology issues. Toigo maintains an information clearinghouse covering data storage and storage management at www.stormgt.org on the World Wide Web.

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POPULATION GROWTH has been thought, since the time of Thomas Malthus, to produce dire consequences such as disease, scarcity and social deviancy. This dark view seemed confirmed by rodent studies. Yet little evidence suggests that people are similarly affected: we seem to handle large crowds quite well for the most part.

Coping with CROWDING

by Frans B. M. de Waal, Filippo Aureli and Peter G. Judge

BRIAN PETERSON *Weststock*

In 1962 this magazine published a seminal paper by experimental psychologist John B. Calhoun entitled "Population Density and Social Pathology." The article opened dramatically with an observation by the late-18th-century English demographer Thomas Malthus that human population growth is automatically followed by increased vice and misery. Calhoun went on to note that although we know overpopulation causes disease and food shortage, we understand virtually nothing about its behavioral impact.

This reflection had inspired Calhoun to conduct a nightmarish experiment. He placed an expanding rat population in a crammed room and observed that the rats soon set about killing, sexually assaulting and, eventually, cannibalizing one another. Much of this activity happened among the occupants of a central feeding section. Despite the presence of food elsewhere in the room, the rats were irresistibly drawn to the social stimulation—even though many of them could not reach the central food dispensers. This pathological togetherness, as Calhoun described it, as well as the attendant chaos and behavioral deviancy, led him to coin the phrase "behavioral sink."

In no time, popularizers were comparing politically motivated street riots to rat packs, inner cities to behavioral sinks and urban areas to zoos. Warning that society was heading for either anarchy or dictatorship, Robert Ardrey, an American science journalist, remarked in 1970 on the voluntary nature of human crowding: "Just as Calhoun's rats freely chose to eat in the middle pens, we freely enter the city." Calhoun's views soon became a central tenet of the voluminous literature on aggression.

In extrapolating from rodents to people, however, these thinkers and writers were making a gigantic leap of faith. A look at human populations suggests why such a simple extrapolation is so problematic. Compare, for instance, per capita murder rates with the number of people per square kilometer in different nations—as we did, using data from the United Nations's *1996 Demographic Yearbook*. If things were straightforward, the two ought to vary in tandem. Instead there is no statistically meaningful relation.

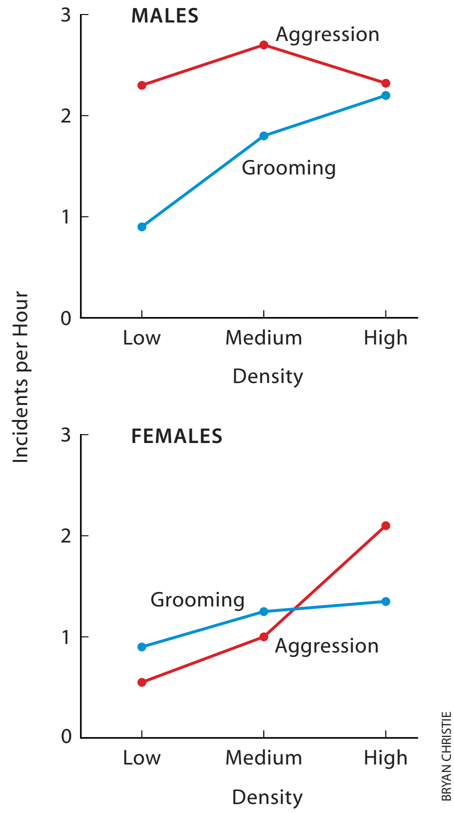
But, one could argue, perhaps such a relation is obscured by variation in national income level, political organization or some other variable. Apparently not, at least for income. We divided the nations into three categories—free-market, former East Block and Third World—and did the analysis again. This time we did find one significant correlation, but it was in the other direction: it showed more violent crime in the least crowded countries of the former East Block. A similar trend existed for free-market nations, among which the U.S. had by far the highest homicide rate despite its low overall population density. The Netherlands had a population density 13 times as high, but its homicide rate was eight times lower.

Knowing that crime is generally more common in urban areas than it is in the countryside, we factored in the proportion of each nation's population that lives in large cities and controlled for it. But this correction did nothing to bring about a positive correlation between population density and homicide. Perhaps because of the overriding effects of history and culture, the link between available space and human aggression—if it exists at all—is decidedly not clear-cut.

Even if we look at small-scale human experiments, we find no supporting evidence. Crowding of children and college students, for instance, sometimes produced irritation and mild aggression, but in general, people seemed adept at avoiding conflict. Andrew S. Baum and his co-workers in the psychiatry department at the Uniformed Services University found that dormitory residents who shared facilities with many people spent less time socializing and kept the doors to their rooms closed more often than did students who had more space. Baum concluded that the effects of crowding are not nearly as overwhelming as originally presumed. Published in the 1980s, these and other findings began to undermine, at least in the scientific community, the idea that people and rats react in the same ways to being packed together. In modern society, people commonly assemble in large masses—during their daily commute to work or during holiday-season shopping expeditions—and most of the time

A persistent and popular view holds that high population density inevitably leads to violence. This myth, which is based on rat research, applies neither to us nor to other primates

FRANS B. M. DE WAAL



SOURCE: Peter G. Judge and Frans B. M. de Waal

RHESUS MONKEYS from three different settings show different rates of grooming—that is, of calming one another. The monkeys seem to adapt to crowded conditions by grooming more frequently. Among the males, grooming of each other and of females was more common when they lived in crowded conditions than when they lived in more spacious quarters. Among female nonkin, aggression was common and increased further with crowding but was accompanied by increased grooming, which served to reduce conflicts.

they control their behavior extraordinarily well.

Calhoun's model, we must conclude, does not generally apply to human behavior. Is this because our culture and intelligence make us unique, or is the management of crowding part of an older heritage? To answer this question, we turn to the primates.

Primates Are Not Rats

Primate research initially appeared to support the harrowing scenario that had been presented for rats. In the 1960s scientists reported that city-dwelling monkeys in India were more aggressive than were those living in forests. Others claimed that monkeys in zoos were excessively violent. Those monkeys were apparently ruled by terrifying bullies who dominated a social hierarchy that was considered an artifact of captivity—in other words, in the wild, peace and egalitarianism prevailed. Borrowing from the hyperbole of popularizers, one study of crowding in small captive groups of baboons even went so far as to report a "ghetto riot."

As research progressed, however, conflicting evidence accumulated. Higher population density seemed to increase aggression occasionally—but the opposite was also true. One report, for instance, described intense fighting and killing when a group of macaques were released into a corral 73 times *larger* than their previous quarters had been. Then, after two and a half years in the corral, a similar increase in aggression occurred when the monkeys were crowded back into a small pen.

Whereas the macaque study manipulated population density through environmental change, other early research did so by adding new monkeys to existing groups. Given the xenophobic nature of monkeys, these tests mainly measured their hostile attitude toward strangers, which is quite different from the effect of density. The better controlled the studies became, the less clear-cut the picture turned out to be. Increased population density led to increased aggression in only 11 of the 17 best-designed studies of the past few decades.

In the meantime, the view of wild primates was changing. They were no longer the purely peaceful, egalitarian creatures people had presumed them to be. In the 1970s field-workers began reporting sporadic but lethal violence in a wide range of species—from macaques to chimpanzees—as well as strict and well-defined hierarchies that remained stable for decades. This view of an often anxiety-filled existence was confirmed when researchers found high levels of the stress hormone cortisol in the blood of wild monkeys [see "Stress in the Wild," by Robert M. Sapolsky; Scientific American, January 1990].

As the view of primates became more complex, and as the rat scenario was weakened by counterexamples, researchers began to wonder whether primates had developed a means to reduce conflict in crowded situations. We saw the first hint of this possibility in a study of the world's largest zoo colony of chimpanzees in Arnhem, the Netherlands. The apes lived on a spacious, forested island in the summer but were packed together in a heated building during the winter. Despite a 20-fold reduction in space, aggression increased only slightly. In fact, the effect of crowding was not entirely negative: friendly grooming and greetings, such as kissing and submissive bowing, increased as well.

We wondered if this conciliatory behavior mitigated tension and proposed a way to test this possibility. Without ignoring the fact that crowding increases the potential for conflict, we predicted that primates employ counterstrategies—including avoiding potential aggressors and offering appeasement or reassuring body contact. Because some of the skills involved are probably acquired, the most effective coping responses would be expected in animals who have experienced high density for a long time. Perhaps they develop a different "social culture" in the same way that people in different places have varying standards of privacy and interpersonal comfort zones. For example, studies show that white North Americans and the British keep greater distances from others during conversations than Latin Americans and Arabs do.

Coping Culture

We set about finding several populations of monkeys that were of the same species but that had been living in different conditions to see if their behavior varied in discernible ways. We collected detailed data on 122 individual rhesus monkeys at three different sites in the U.S.: in relatively cramped outdoor pens at the Wisconsin primate center in Madison, in large open corrals at the Yerkes primate center in Atlanta and on Morgan Island off the coast of South Carolina. These last monkeys had approximately 2,000 times more space per individual than the highest-density groups. All three groups had lived together for many years, often for generations, and included individuals of both sexes. All the groups had also been in human care, receiving food and veterinary treatment, making them comparable in that regard as well.

Rhesus society typically consists of a number of subgroups, known as matrilines, of related females and their offspring. Females remain together for life, whereas males leave their natal group at puberty. Rhesus monkeys make a sharp distinction between kin and nonkin: by far the most friendly contact, such as grooming, takes place within the matrilines. Females of one matriline also fiercely support one another in fights against other matrilines. Because of their strict hierarchy and pugnacious temperament, rhesus seemed to be ideal subjects. We figured that if this aggressive primate showed coping responses, our hypothesis would have withstood its most rigorous test.

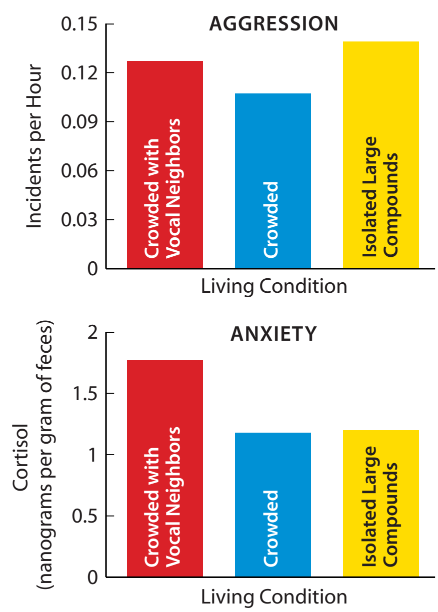
Our first finding was, surprisingly, that density did not affect male aggressiveness. Adult males increasingly engaged in friendly contact under crowded conditions. They groomed females more, and likewise the females groomed the males more frequently. (Grooming is a calming behavior. In another study, we demonstrated that a monkey's heart rate slows down when it is being groomed.) Females also bared their teeth more often to the males—the rhesus way of communicating low status and appeasing potentially aggressive dominant monkeys.

Females showed a different response with other females, however. Within their own matrilines they fought more but did not change the already high level of friendly interaction. In their dealings with other matrilines, they also showed more aggression—but here it was cou-

FRANS B. M. DE WAAL

CHIMPANZEES IN THE WILD have hostile territorial relations with other groups, and in captivity they are bothered by the presence of noisy neighboring chimps. By examining apes under three conditions—those living in a crowded space and able to hear their neighbors, those living in a crowded space without such worrisome sounds, and those living in isolated large compounds (*photograph below*)—we were able to measure the association between aggression, space and stress. Aggression (*photograph at left*) remained the same, but stress varied with neighbors' noise. Chimpanzees in small spaces exposed to vocalizations from other groups showed the highest levels of the stress hormone cortisol.

FRANS B. M. DE WAAL



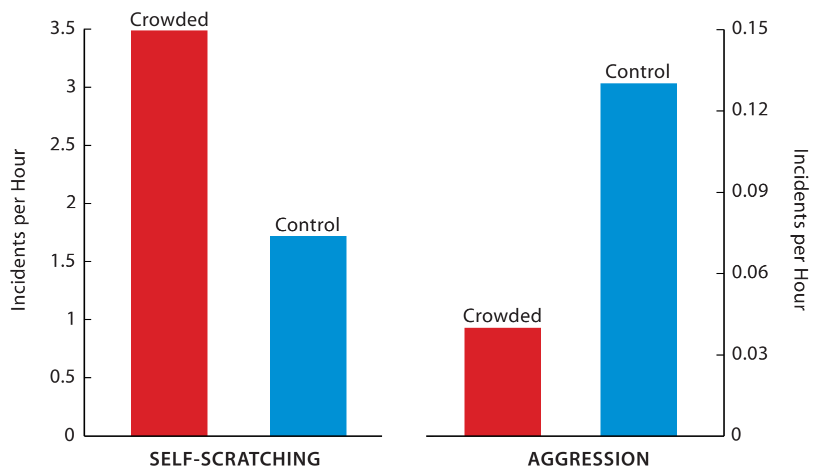
SOURCE: Filippo Aureli and Frans B. M. de Waal

BRYAN CHRISTIE

pled with more grooming and submissive grinning.

These findings make sense in light of the differences between kin and non-kin relationships. Related females—such as sisters and mothers and daughters—are so strongly bonded that their relationships are unlikely to be disrupted by antagonism. Rhesus monkeys are used to managing intrafamilial conflict, cycling through fights and reconciliations, followed by comforting contact. Crowding does little to change this, except that they may have to repair frayed family ties more often. Between matrilines, on the other hand, crowding poses a serious challenge. Normally, friendly contact between matrilines is rare and antagonism common. But reduced escape opportunities make the risk of escalated conflict greater in a confined space. And our data indicated that female rhesus monkeys make a concerted effort at improving these potentially volatile relationships.

CHUCK SAVAGE *The Stock Market*



SOURCE: Filippo Aureli and Frans B. M. de Waal

BRYAN CHRISTIE

Emotions in Check

In a second project, we turned our attention to chimpanzees. As our closest animal relatives, chimpanzees resemble us in appearance, psychology and cognition. Their social organization is also humanlike, with well-developed male bonding—which is rare in nature—reciprocal exchange and a long dependency of offspring on the mother. In the wild, male chimpanzees are extremely territorial, sometimes invading neighboring territories and killing enemy males. In captivity such encounters are, of course, prevented.

We collected data on more than 100 chimpanzees in various groups at the Yerkes primate center. Although some groups had only a tenth the space of others, cramped quarters had no measurable impact on aggression. In contrast to the monkeys, chimpanzees maintained their grooming and appeasement behavior—no matter the situation. If crowding did induce social tensions, our chimpanzees seemed to control them directly.

We usually do not think of animals as holding in their emotions, but chimpanzees may be different. These apes are known for deceptive behavior—for instance, they will hide hostile intentions behind a friendly face until an adversary has come within reach. In our study, emotional control was reflected in the way chimpanzees responded to the vocalizations of neighboring groups. Such noises commonly provoke hooting and charging displays, which in wild chimpanzees serve to ward off territorial intrusion.

In a confined space, however, excited reactions trigger turmoil within the group. We found that chimpanzees in the most crowded situations had a three times *lower* tendency to react to neighbors' vocalizations than chimpanzees with more space did. Chimpanzees may be smart enough to suppress responses to external stimuli if those tend to get them into trouble. Indeed, field-workers report that chimpanzee males on territorial patrol suppress all noise if being detected by their neighbors is to their disadvantage.

The inhibition of natural responses is not without cost. We know that continuous stress has the potential to suppress the immune system and therefore has important implications for health and longevity. We developed two noninvasive techniques to measure stress in our chimpanzees. One was to record the rate of self-scratching. Just as with college students who scratch their heads when faced with a tough exam question, self-scratching indicates anxiety in other primates. Our second technique was to collect fecal samples and analyze them for cortisol. Both measures showed that groups of chimpanzees who had little

FRANS B.M. DE WAAL

ELEVATOR EFFECT helps to explain how chimpanzees, and people, deal with crowding. During brief periods of crowding, people often limit social interaction—a way of avoiding any conflict (*photograph at left*). Chimpanzees do the same, reducing their aggressive interactions (*photograph above* and *chart at left*). This doesn't mean that crowded situations do not induce anxiety. Chimpanzees packed together tend to scratch themselves more often—a sign of stress.

space and heard neighbors' vocalizations experienced more stress. Space by itself was not a negative factor, because in the absence of noisy neighbors, chimpanzees in small spaces showed the same stress level as those with a good deal of space.

So even though chimpanzees fail to show a rise in aggression when crowded, this does not necessarily mean that they are happy and relaxed. They may be working hard to maintain the peace. Given a choice, they would prefer more room. Every spring, when the chimpanzees at the Arnhem zoo hear the door to their outdoor island being opened for the first time, they fill the building with a chorus of ecstasy. They then rush outside to engage in a pandemonium in which all of the apes, young and old, embrace and kiss and thump one another excitedly on the back.

The picture is even more complex if we also consider short periods of acute crowding. This is a daily experience in human society, whether we find ourselves on a city bus or in a movie theater. During acute crowding, rhesus monkeys show a rise in mild aggression, such as threats, but not violence. Threats serve to keep others at a distance, forestalling unwanted contact. The monkeys also avoid one another and limit active social engagement, as if they are trying to stay out of trouble by lying low.

Chimpanzees take this withdrawal tactic one step further: they are actually less aggressive when briefly crowded. Again, this reflects greater emotional restraint. Their reaction is reminiscent of people on an elevator, who reduce frictions by minimizing large body movements, eye contact and loud verbalizations. We speak of the elevator effect, therefore, as a way in which both people and other primates handle the risks of temporary closeness.

Our research leads us to conclude that we come from a long lineage of social animals capable of flexibly adjusting to all kinds of conditions, including unnatural ones such as crowded pens and city streets. The adjustment may not be without cost, but it is certainly preferable to the frightening alternative predicted on the basis of rodent studies.

We should add, though, that even the behavioral sink of Calhoun's rats may not have been entirely the product of crowding. Food competition seemed to play a role as well. This possibility contains a serious warning for our own species in an ever more populous world: the doomsayers who predict that crowding will inevitably rip the social fabric may have the wrong variable in mind. We have a natural, underappreciated talent to deal with crowding, but crowding combined with scarcity of resources is something else. SA

The Authors

FRANS B. M. DE WAAL, FILIPPO AURELI and PETER G. JUDGE share a research interest in the social relationships and behavioral strategies of nonhuman primates. Their work on aspects of this topic will appear in *Natural Conflict Resolution,* to be published by the University of California Press. De Waal, author of *Chimpanzee Politics* and *Good Natured,* worked for many years at the Arnhem zoo in the Netherlands before coming to the U.S., where he is now director of the Living Links Center at the Yerkes Regional Primate Research Center in Atlanta and professor of psychology at Emory University. Aureli is a senior lecturer in biological and earth sciences at Liverpool John Moores University in England. Judge is an assistant professor at Bloomsburg University in Pennsylvania and a research associate at Yerkes.

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Making METALLIC

By re-creating extreme conditions like those in Jupiter's core, physicists have at long last turned hydrogen into a metal

by William J. Nellis

The two-stage gas gun at Lawrence Livermore National Laboratory is about as long as two city buses and contains enough hydrogen gas to explode with the power of 10 sticks of dynamite. It fires projectiles at up to seven kilometers per second—more than 20 times the velocity of sound and some 15 times faster than a speeding bullet. This device is not a weapon, though: it is a powerful experimental tool, and its target is merely a few drops of liquid.

Of course, it's no ordinary liquid, even if it is the most common element in the universe. Despite its simple atomic structure—only one proton and one electron—hydrogen has proved to be much more complicated than scientists had imagined. Ordinarily a gas consisting of diatomic (two-atom) molecules, hydrogen can be cooled to a liquid (below 20 kelvins, or –253 degrees Celsius) and a solid (below 14 kelvins). In all these states, hydrogen is normally an electrical insulator, but in the 1930s physicists predicted that subjecting hydrogen to extreme pressure would cause the molecules to dissociate—break apart into atoms—turning the substance into a conductive metal.

What is more, in the 1960s Neil W. Ashcroft of Cornell University posited that solid metallic hydrogen would conduct electricity without resistance. If it could be stabilized so that it remained metallic under ordinary conditions, it might be used as a room-temperature superconductor—a material that physicists have been seeking for decades. It might also serve as a compact energy source and as a lightweight building material.

My colleagues and I have recently taken a step toward realizing those possibilities. Using the Livermore gas gun, we managed to compress liquid hydrogen sufficiently so that it turned into a liquid metal. It remained in that state for less than one millionth of a second, but that was long enough to take measurements and to determine the material's electrical conductivity. Although the goal of creating solid metallic hydrogen has not yet been achieved, our results provide insight into the behavior of hydrogen at various ultrahigh pressures and temperatures. This knowledge may help researchers devise better means to initiate fusion reactions for energy production. It may also advance our understanding of the interior of Jupiter, which is so massive that fluid hydrogen inside the gas giant is believed to be squeezed into metallic form.

At the close of the 19th century, several scientists had predicted that hydrogen, when condensed, would become metallic. After all, it resides in the first column of the periodic table, with the alkali metals. In 1898 Scottish physicist James Dewar liquefied hydrogen and, a year later, solidified it. To the surprise of many, both condensed phases turned out to be insulators: the hydrogen atoms remained bound in diatomic molecules and behaved like the halogens in the seventh column of the periodic table, such as chlorine and fluorine.

But as quantum mechanics—the physics of the atom-size world—began to develop, new analyses of hydrogen emerged. In 1935 Eugene P. Wigner of Princeton University predicted that the insulating diatomic molecular solid would transform to a metallic monatomic solid at sufficiently high pressure. Over the years the theoretical estimates of the required pressure have varied from 25 to 2,000 gigapascals, or from about 250,000 to 20 million times the atmospheric pressure at sea level. According to the most recent calculations, solid molecular hydrogen might become metallic just above 400 gigapascals, or about four million atmospheres. New x-ray measurements, however, indicate that the transition pressure might be as high as 620 gigapascals.

One way to achieve such a high pressure—about equal to that at Earth's center—is to squeeze a sample between two superhard surfaces. The diamond-anvil cell uses this approach [see "The Diamond-Anvil High-Pressure Cell," by A. Jayaraman; Scientific American, April 1984]. Researchers have achieved pressures of up to 500 gigapascals with it.

Working with this device, Russell J. Hemley and Ho-kwang Mao of the Carnegie Institution of Washington, Isaac F. Silvera of Harvard University and Arthur L. Ruoff of Cornell have attempted to metallize hydrogen by subjecting it to pressures up to 340 gigapascals. Although the hydrogen solidified, permitting x-ray diffraction and spectroscopic measurements, the researchers have not been able to detect the conductivity of the material directly, because the electrical

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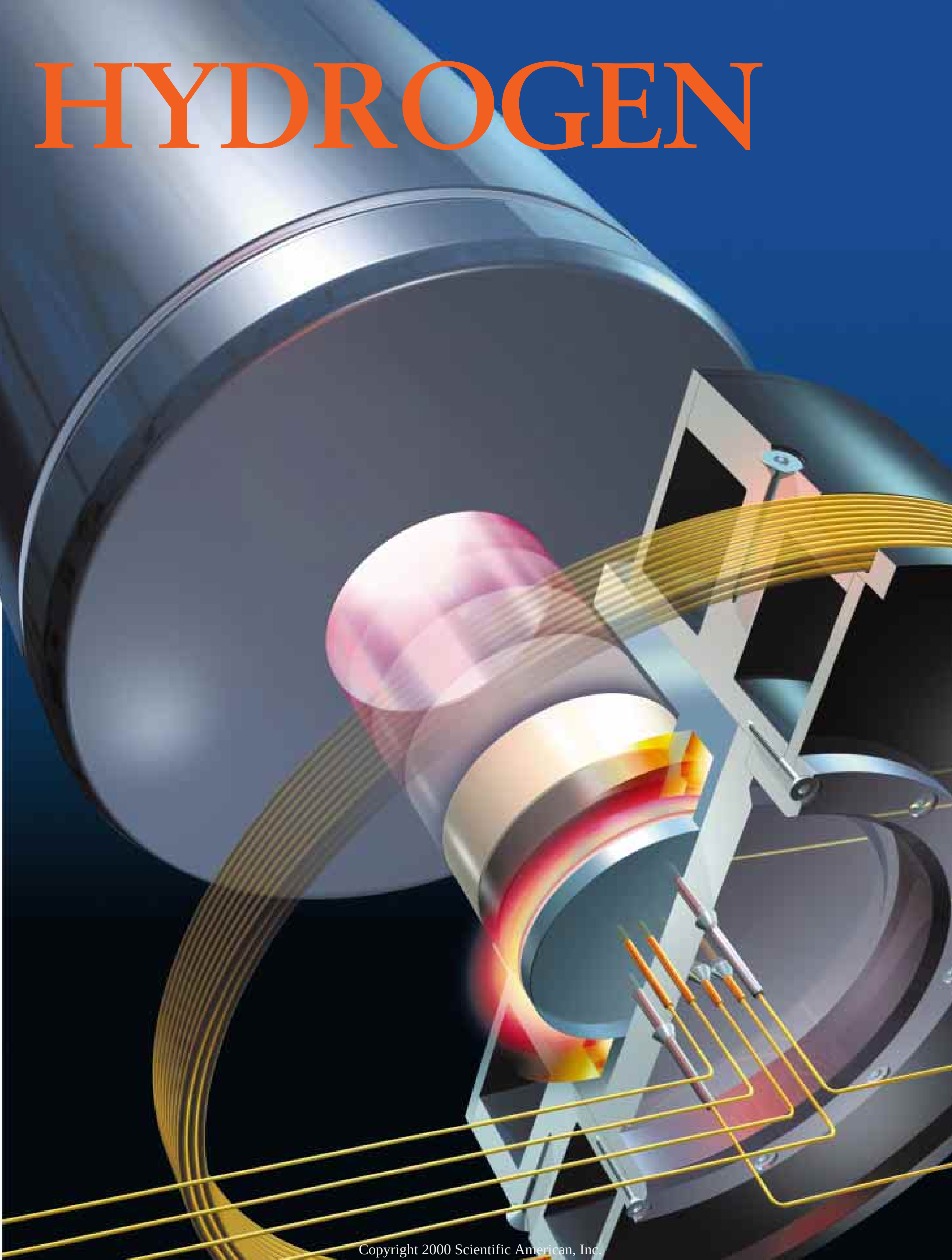
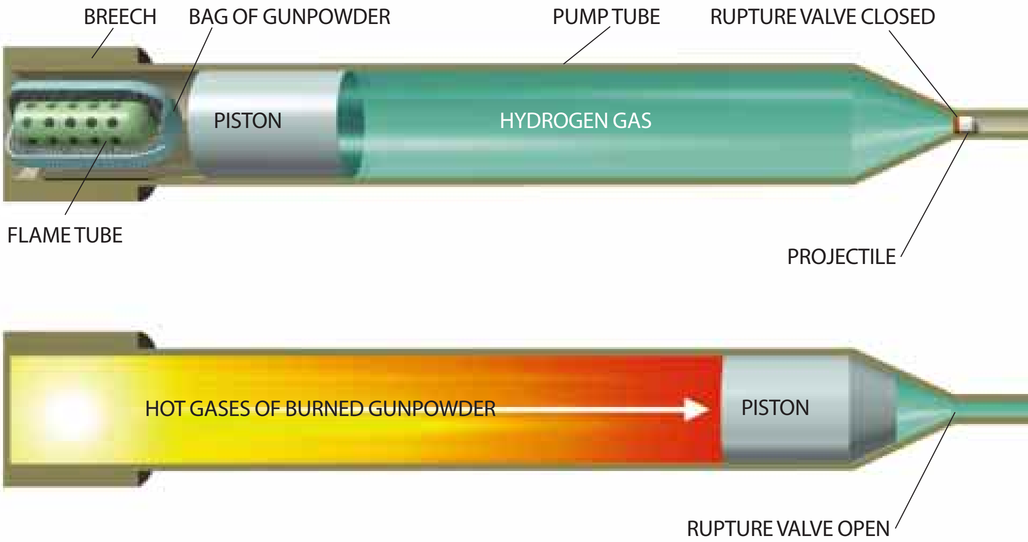
SUDDEN IMPACT provides the shock pressure needed to squeeze a sample of liquid hydrogen into a metallic state. A gas gun (*top*) accelerates a projectile—a quarter-size metal disk with a plastic backing—to speeds as high as seven kilometers per second. When the projectile strikes the sample holder (*shown in cutaway at bottom*), it creates a shock wave in the thin layer of liquid hydrogen (*yellow*). The wave reverberates between two hard sapphire plates (*blue*), subjecting the hydrogen to pressures of up to 180 gigapascals. The trigger pins (*purple*) turn on the recording equipment, and the electrodes (*orange*) measure the hydrogen's conductivity to determine when it becomes metallic.

HYDROGEN



TWO-STAGE GAS GUN consists of a breech, a pump tube and a narrower barrel. Before firing, the breech holds up to 3.3 kilograms of gunpowder, with some in a hollow flame tube and the rest in a bag around the tube (*top*). When the gunpowder is ignited, the hot gases from the explosion push a piston down the pump tube (*bottom*). The piston compresses the hydrogen gas in front of it; the gas then ruptures a valve and rushes into the barrel, pushing a projectile toward the target chamber. The projectile is a metallic impactor plate embedded in a plastic cylinder. It strikes the aluminum sample holder containing the liquid hydrogen that is to be metallized (*far right*).



leads in the diamond-anvil cell have broken under the high pressure. It has also not been possible to metallize liquid hydrogen in the diamond-anvil cell, because the fluid rapidly diffuses through the walls of the device.

Hydrogen Gunslinging

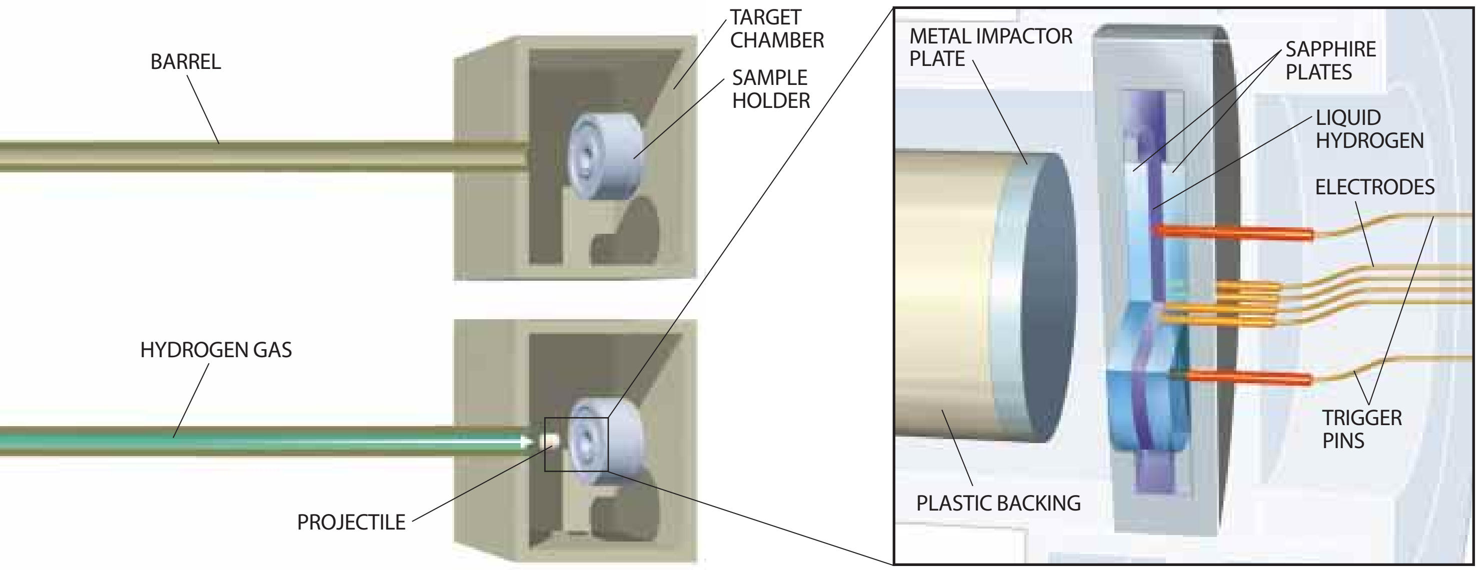
The approach using the gas gun began about 10 years ago, shortly after the discovery of high-temperature superconductors. These ceramiclike materials conduct electricity without resistance at temperatures near the boiling point of nitrogen (about 77 kelvins, or –196 degrees C)—far higher than the temperatures needed for traditional superconductors (near helium's boiling point of about four kelvins). In the early 1990s I started using the gas gun to investigate these materials. The gun itself was developed by General Motors for ballistic-missile research during the 1960s; a larger version of the gun was used to accelerate models of the missiles and thus simulate the effects of high-velocity atmospheric reentry. Livermore eventually came to own the smaller gun, which is useful in defense research because it can expose materials to extreme conditions.

Knowing the kinds of pressures the gun was capable of achieving, I speculated that it might be useful for studying the conductivity of fluid hydrogen. When hydrogen is subjected to high pressure, its melting point rises, reaching 1,500 kelvins (more than 1,200 degrees C) when the pressure is at 100 gigapascals. So the fluid must be heated to keep it from solidifying. An ideal way both to squeeze and to heat the hydrogen is with a shock wave. More familiar as the sonic boom initiated by faster-than-sound aircraft, a shock wave is a sudden change in pressure that forces molecules together very rapidly, thus raising their temperature. In 1991 my colleagues Samuel T. Weir, Arthur C. Mitchell and I began using the gas gun to produce a reverberating shock wave in liquid hydrogen.

The first stage of the gun consists of a breech containing up to 3.3 kilograms of gunpowder, which drives a heavy piston down a pump tube 10 meters long and 90 millimeters in diameter [*see illustration above*]. Sixty grams of hydrogen gas (not to be confused with the hydrogen to be metallized) fills this tube. The piston, weighing up to 6.8 kilograms, squeezes the hydrogen ahead of it. When the gas attains a pressure of about 0.1 gigapascal, it ruptures a valve and enters the gun's second stage, con-

COURTESY OF WILLIAM J. NELLIS

HIGH-PRESSURE RESEARCHERS pose next to the gas gun used to metallize liquid hydrogen at Lawrence Livermore National Laboratory. From left to right, the scientists are Arthur C. Mitchell, Samuel T. Weir and William J. Nellis.



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sisting of a narrower, evacuated barrel nine meters long and 28 millimeters in diameter. A narrower barrel is important because the drop in volume causes the gas to speed up.

Once past the valve, the gas pushes a quarter-size metal plate called the impactor. (Hydrogen accelerates the projectile best because it has the lowest molecular weight and highest sound speed of any gas.) The 20-gram impactor travels down the barrel at speeds up to seven kilometers per second, or 16,000 miles per hour. At the end of the barrel it strikes an aluminum sample holder containing the liquid hydrogen, which occupies a 0.5-millimeter-thick layer sandwiched between two hard sapphire plates. The fluid has been cooled to 20 kelvins to obtain a high initial density.

The impact generates a strong shock wave that passes through the aluminum container and into the liquid hydrogen. The sapphire plates reflect the shock wave, causing it to reverberate more than 10 times between them. This process creates shock pressures as high as 180 gigapascals in the hydrogen, compressing the fluid to one tenth its original volume and raising its temperature to 3,000 kelvins. The reverberation and accumulation of the shock wave and its pressure are the keys to the experiment's success; subjecting the hydrogen to a single shock wave with the same pressure would raise the fluid's temperature much too high.

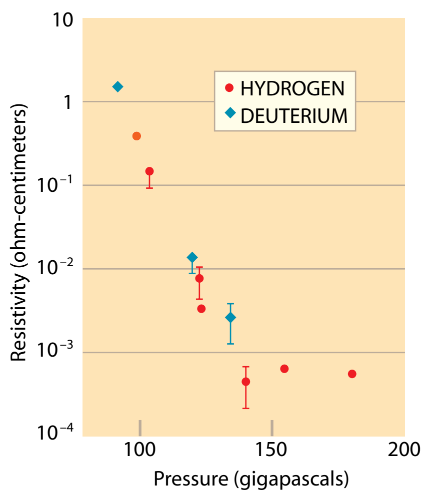
A trigger pin in the sample holder turns on the recording equipment once it detects that the first shock wave has entered the hydrogen. Although the sample is subjected to the maximum pressure for only about 100 nanoseconds (one tenth of one millionth of a second), this time is long enough for the hydrogen to reach thermal equilibrium and for us to conduct measurements. Fortunately, the duration of the experiment is also short enough that the hydrogen does not have time to diffuse out of its holder or react chemically with it.

The experiment was not without its dangers. Precautions had to be taken to ensure that the hydrogen gas in the gun did not mix with oxygen in the target chamber. If all the hydrogen in the gun reacted with oxygen, the energy released would be equivalent to an explosion of two kilograms of TNT. So we made sure the target chamber was strong enough to endure shrapnel from the impact, because a punctured chamber would permit air (and oxygen) to enter. We also designed the experiment so that if air did leak in, it would not be enough to set off an explosion. All the voltages used for diagnostics in the target chamber were shut down right after the gun was fired, so that no sparks could ignite the hydrogen. In addition, nitrogen gas was rapidly pumped into the target chamber after each firing to render the hydrogen inert. Finally, no one was allowed in the room when the gun was fired.

Our discovery of metallic hydrogen was serendipitous—we had expected to see fluid hydrogen approach a metallic state but not actually reach it. To determine the conductivity of the liquid hydrogen, we sent a small amount of current to electrodes in the sample holder, which enabled us to measure the hydrogen's electrical resistivity. (The resistance of a wire to an electric current is equal to its resistivity multiplied by its length and divided by its cross-sectional area.) We found that at a pressure of 93 gigapascals the resistivity of the liquid hydrogen was about one ohm-centimeter and that increasing the pressure to 120 gigapascals lowered the resistivity to about 0.005 ohm-centimeter. These values correspond to a semiconducting state; the resistivities are lower than those of typical insulators but higher than those of metallic conductors.

When we increased the pressure to 140 gigapascals, however, the resistivity of the liquid hydrogen decreased to about 0.0005 ohm-centimeter, indicat-

RESULTS of the gas gun experiments show how the resistivity of liquid hydrogen drops—and hence its conductivity rises—as researchers increase the pressure on the sample. At pressures of 93 to 120 gigapascals, liquid hydrogen is in a semiconducting state, but at a pressure of 140 gigapascals, the resistivity drops to about 0.0005 ohm-centimeter, and the hydrogen becomes metallic. The results for deuterium, a hydrogen isotope, follow the same pattern.



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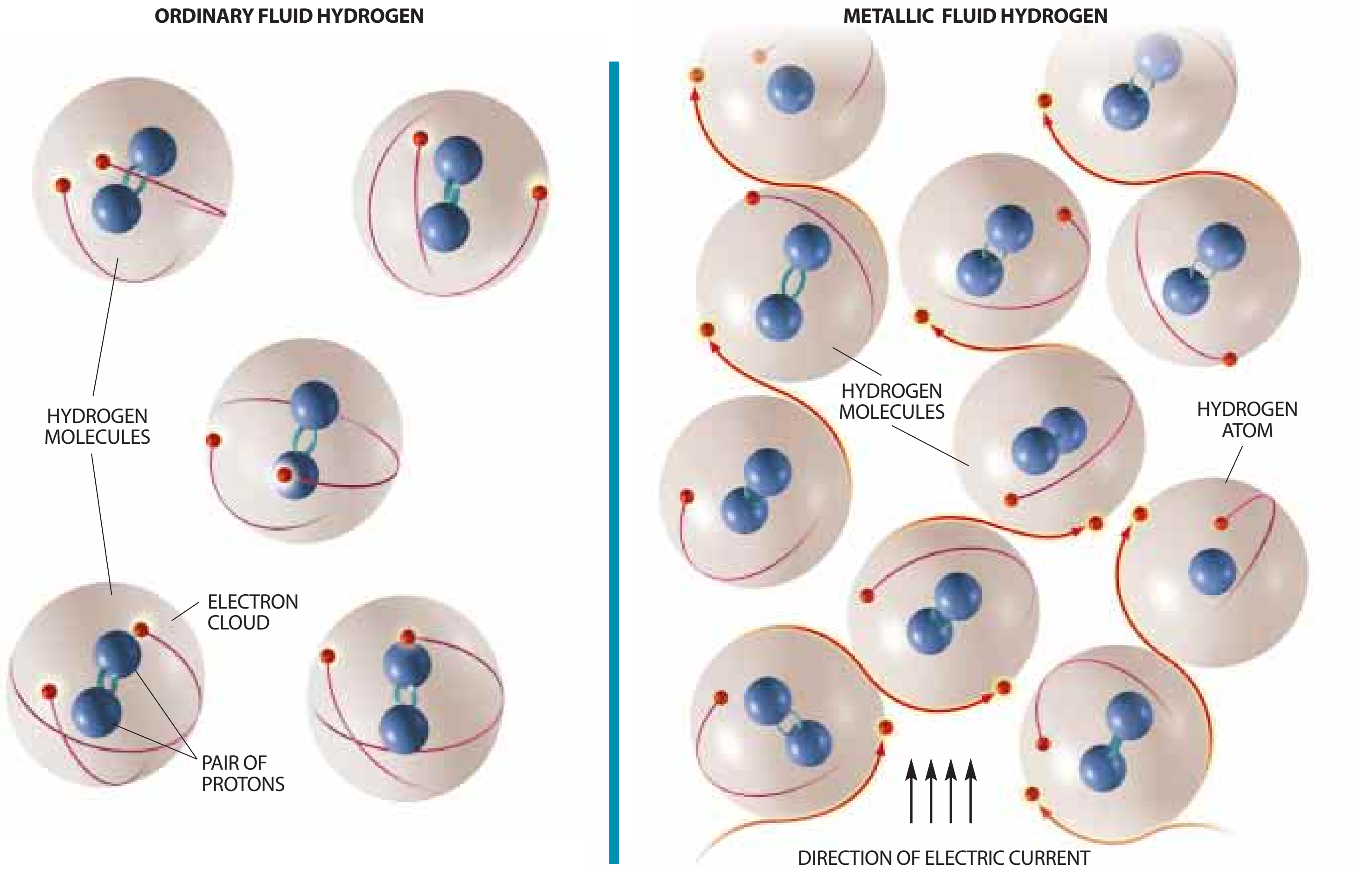


MOLECULES in ordinary liquid hydrogen (*left*) are well separated, and the electrons—shown as clouds of negative charge—stay close to the pairs of protons. But high pressure pushes the molecules so close to one another that the electrons can easily hop from one molecule to the next, thus creating an electric current when a voltage is applied to the liquid (*right*). The pressure also causes about 10 percent of the molecules to break apart into atoms.

ing that it was in a fully conducting metallic state. The resistivity remained at that level for the higher pressures we tested (up to 180 gigapascals). I was so surprised by these results that I held off publishing the data. I spent a year double-checking the findings until I could understand why the resistivity should stay constant at the higher pressures.

On the atomic scale, what happens during metallization is that some of the hydrogen's electrons are freed from their molecules [*see illustration above*]. At low pressures, the tendency for two hydrogen atoms to form a molecule is extremely strong, so the liquid hydrogen contains only molecules. Each molecule contains a pair of protons surrounded by a cloud of negative charge. Because it takes a relatively large amount of energy—15 electron volts—to remove an electron from a hydrogen molecule, the molecular hydrogen fluid cannot carry a current: it is electrically insulating.

This situation changes, however, as the hydrogen molecules are pushed together and heated by the reverberating shock wave. The electronic mobility gap—the energy required to remove an electron from a molecule so that it can conduct an electrical charge—decreases as the molecules move closer together. What is more, the energy needed to remove the electrons is provided by the shock heating. In this state the fluid hydrogen is semiconducting—its electrical conductivity steadily rises (and its resistivity steadily drops) with increasing density and temperature.

When we increased the shock pressure to 140 gigapascals, the density of the liquid hydrogen rose to 0.32 mole per cubic centimeter, the temperature climbed to 2,600 kelvins, and the electronic mobility gap dropped to just 0.22 electron volt. At this density, the hydrogen molecules are so close to one another that their clouds of negative charge overlap, allowing the electrons to hop freely from one molecule to the next. The electrons are now mobile, and further increases in density do not make them any more so, which explains why the hydrogen's resistivity does not continue to decrease at higher pressures.

In addition, under these conditions about 10 percent of the hydrogen molecules break apart into atoms. The fluid hydrogen becomes a complex mixture of molecules, atoms and probably higher-order clusters. Collisions of molecules constantly break them into atoms, which eventually recombine to form new molecules. Because of the disorder in the fluid, the conducting electrons are scattered at each molecule. This state is called the minimum conductivity of a disordered metal.

The pressure required to metallize hydrogen in the solid state is higher than that needed for the fluid. This is probably because the hydrogen atoms, on solidifying, lock themselves into a crystalline lattice, which inhibits metallization by increasing the electronic energy gap. In liquids, no such structure exists.

The data on electrical conductivities and on hydrogen's behavior at ultrahigh pressures and temperatures have proved illuminating. In particular, they have implications for models of the interiors of

Jupiter and Saturn. Together these gas giants are more than 400 times as massive as Earth. Much of their hydrogen exists in the form of metallic fluid, which produces the magnetic fields of these planets by convective dynamo action.

Jupiter in a Bottle

For example, before our results, planetary scientists theorized that Jupiter, beneath its thick clouds, has a mantle of electrically insulating liquid hydrogen extending a quarter of the way to the planet's center (about 18,000 kilometers down) and a core of metallic liquid hydrogen. In this model, there is a sharp boundary between the mantle and the core; at that depth, the gravitational pressure (about 300 gigapascals) transforms the hydrogen from a diatomic insulating fluid to a monatomic metallic fluid. Our laboratory results, however, indicate that the transition between molecular and monatomic hydrogen is continuous in the fluid. It is therefore unlikely that there is a distinct boundary between Jupiter's mantle and core. Molecular hydrogen probably begins to dissociate at a pressure of about 40 gigapascals and breaks apart completely at about 300 gigapascals. The electrical conductivity reaches the minimum level for a metal at 140 gigapascals and 4,000 kelvins. This pressure would occur at a depth of only about 7,000 kilometers.

Thus, Jupiter's magnetic field is produced much closer to the surface than was previously thought, which would explain why the planet's surface field, about 10 gauss, is relatively large. In comparison, Earth's magnetic field is produced much deeper inside the planet—in the iron core, which extends only halfway to the surface—so the surface field is only about 0.5 gauss.

Knowing how fluid hydrogen behaves over a wide range of temperatures and pressures is also important for the development of inertial-confinement fusion (ICF). In ICF, a fuel pellet composed of the hydrogen isotopes deuterium and tritium is placed in a specially shaped cavity called a hohlraum and is radiated by high-intensity, temporally stepped laser pulses. The first laser pulse produces a shock wave of about 100 gigapascals, and the successive pulses act like the reverberating shock waves of our experiment. For ICF researchers, knowing how hydrogen reacts to these pressures enables them to determine the best way to administer the laser pulses.

The Myriad Uses of Metallic Hydrogen

In our experiments the liquid hydrogen remained in a metallic state for less than a microsecond. But if researchers could create solid metallic hydrogen and preserve it in that state under ordinary conditions—that is, room temperature and ambient pressure—the potential scientific and technological benefits would be enormous. Because it is not known how, nor even whether, metallic hydrogen could be made to last in ambient conditions, the following is pure speculation. In general, the electrical, magnetic, optical, thermal and mechanical properties of such a substance would probably be unusual. Here are some of the possible applications of solid metallic hydrogen:

Room-temperature superconductor

Some physicists have predicted that solid metallic hydrogen would be able to transmit electricity without resistance at room temperature. Such a superconductor could revolutionize most aspects of modern life: transmission lines would not lose energy, computers would run faster, trains could be levitated on magnetic cushions, and vast amounts of energy could be stored in magnetic fields without appreciable loss. The best high-temperature superconductors now work at about 150 kelvins (–123 degrees Celsius) and must be cooled with liquid nitrogen, making them impractical for everyday uses.

Lightweight structures

Metallic hydrogen might be made strong and stable through the use of additives, which would bond to the hydrogen molecules and atoms while they were under ultrahigh pressure. The temperature and pressure would then be quickly lowered. This rapid quenching would most likely result in a metallic glass, perhaps similar to the palladium metallic glass made today using boron and phosphorus as additives. Solid metallic hydrogen would probably have a density comparable to its liquid counterpart, about 0.7 gram per cubic centimeter, or nearly the same density as water. The substance would be three times lighter than aluminum and about 10 times lighter than iron. It is impossible, though, to predict its strength. In the most optimistic scenario, solid metallic hydrogen could be used to build lightweight automobiles, which would be much more fuel-efficient than conventional vehicles.

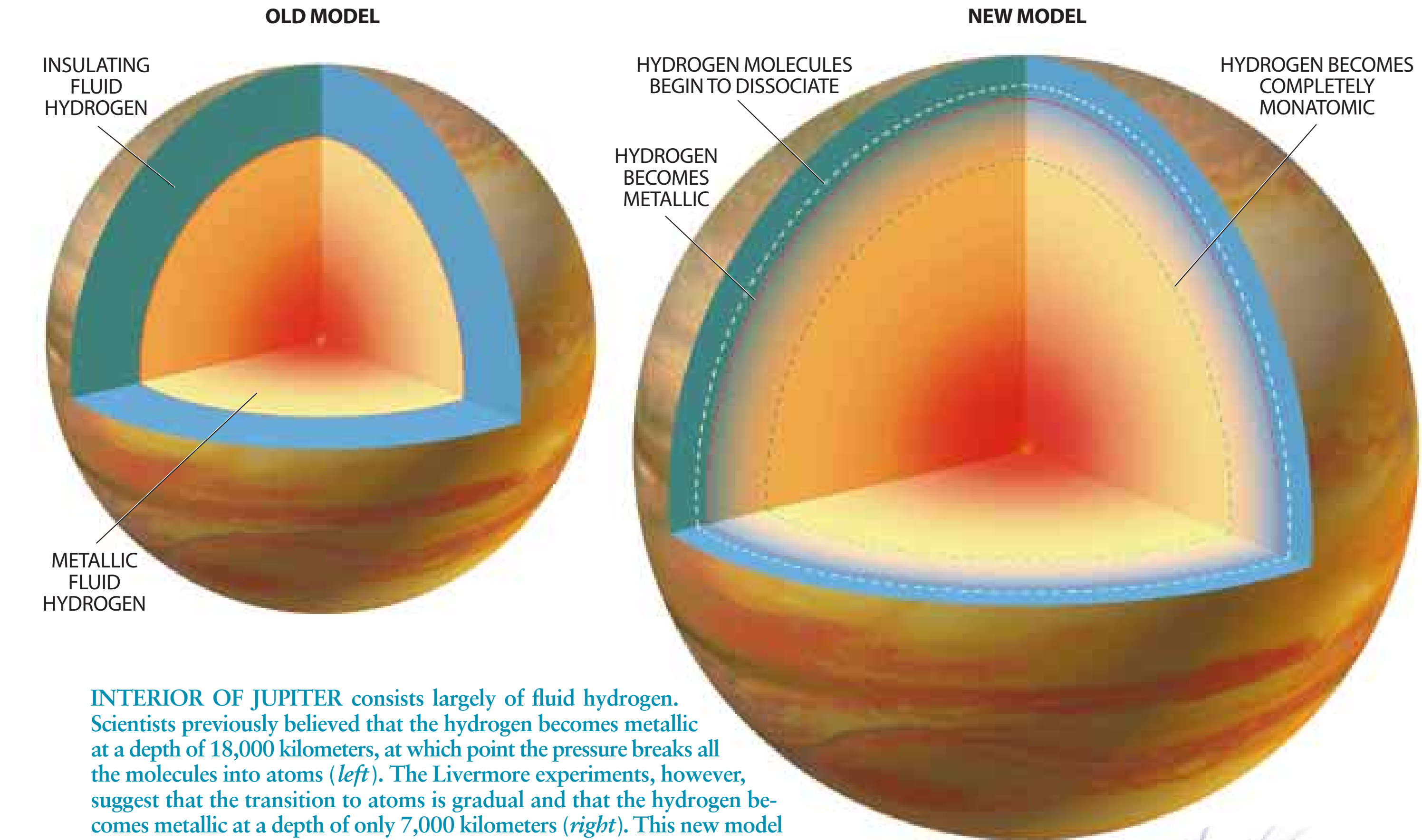
Clean fuel

Because of its density, solid metallic hydrogen could store a large amount of energy, which would be released when the solid reverted to the gas phase. We cannot estimate the efficiency of such a process, but we know the primary product of this reaction would be hydrogen gas, so solid hydrogen fuel would be environmentally clean, provided that the additives required to synthesize it are. If this energy could be released relatively slowly, solid metallic hydrogen might replace gasoline and other transportation fuels. If the energy could be released somewhat faster, it might be used as a propellant; for example, solid metallic hydrogen could produce about five times as much thrust per kilogram as the liquid hydrogen-oxygen fuel now used to launch rockets. If the stored energy could be released extremely rapidly, solid metallic hydrogen could be used as an explosive.

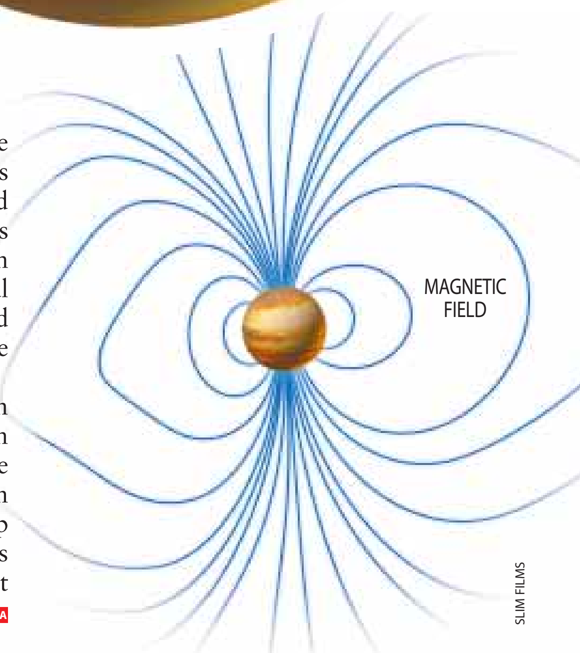
Fusion pellet

Hydrogen in the form of deuterium and tritium (DT) acts as the fuel in inertial-confinement fusion. Powerful lasers compress and heat this fuel, causing the nuclei to fuse. A fuel pellet composed of solid metallic hydrogen would produce much higher fusion energy yields than other forms of DT would, not because it is metallic but because of its high density. Using metallic DT, engineers could pack substantially more fuel into a given space than they could using targets containing gases or cryogenic molecular solids. In addition, the high initial density of the metallic DT pellet would substantially increase the efficiency of the process.

—W.J.N.



INTERIOR OF JUPITER consists largely of fluid hydrogen. Scientists previously believed that the hydrogen becomes metallic at a depth of 18,000 kilometers, at which point the pressure breaks all the molecules into atoms (*left*). The Livermore experiments, however, suggest that the transition to atoms is gradual and that the hydrogen becomes metallic at a depth of only 7,000 kilometers (*right*). This new model would explain why Jupiter has such a strong magnetic field (*below right*).



Our experiments are still far from realizing one of the most interesting speculations: that solid metallic hydrogen, once produced, can remain in that state even at ambient pressure and room temperature. It might be possible to squeeze hydrogen and then quickly release the pressure so that it would retain its metallic properties as a solid, much as carbon squeezed into a diamond retains its crystalline structure after the pressure is removed. Such a material would have innumerable applications [*see box on preceding page*].

The task will be difficult, though, because hydrogen exhibits strong van der Waals forces—that is, the molecules tend to push away from one another once the external pressure is released. What is probably needed are additives that bond to the hydrogen molecules and atoms under pressure and then hold them in place once the pressure is gone. The goal would be to find additives that would not alter the beneficial properties of the metallic hydrogen.

Future experiments with the gas gun might indicate how to do that. But even if they don't, we are sure to learn more about the unusual features of hydrogen under extreme pressures. We can't help but be fascinated by a substance that is at once the universe's simplest element and one of its most complex. SA

The Author

WILLIAM J. NELLIS is a physicist at Lawrence Livermore National Laboratory in Livermore, Calif. He received his Ph.D. in physics from Iowa State University in 1968. His work has focused on the investigation of materials during and after high-pressure shock compression, including the measurement of electrical conductivities, temperatures, equation-of-state data, shock-wave profiles, and phase transitions in liquids and solids. In 1997 he won the Shock Compression Science Award of the American Physical Society for pioneering experimental investigations of molecular and planetary fluids.

Further Information

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More information on metallic hydrogen is available at www-phys.llnl.gov/H_Div/GG/Nellis.html on the World Wide Web.

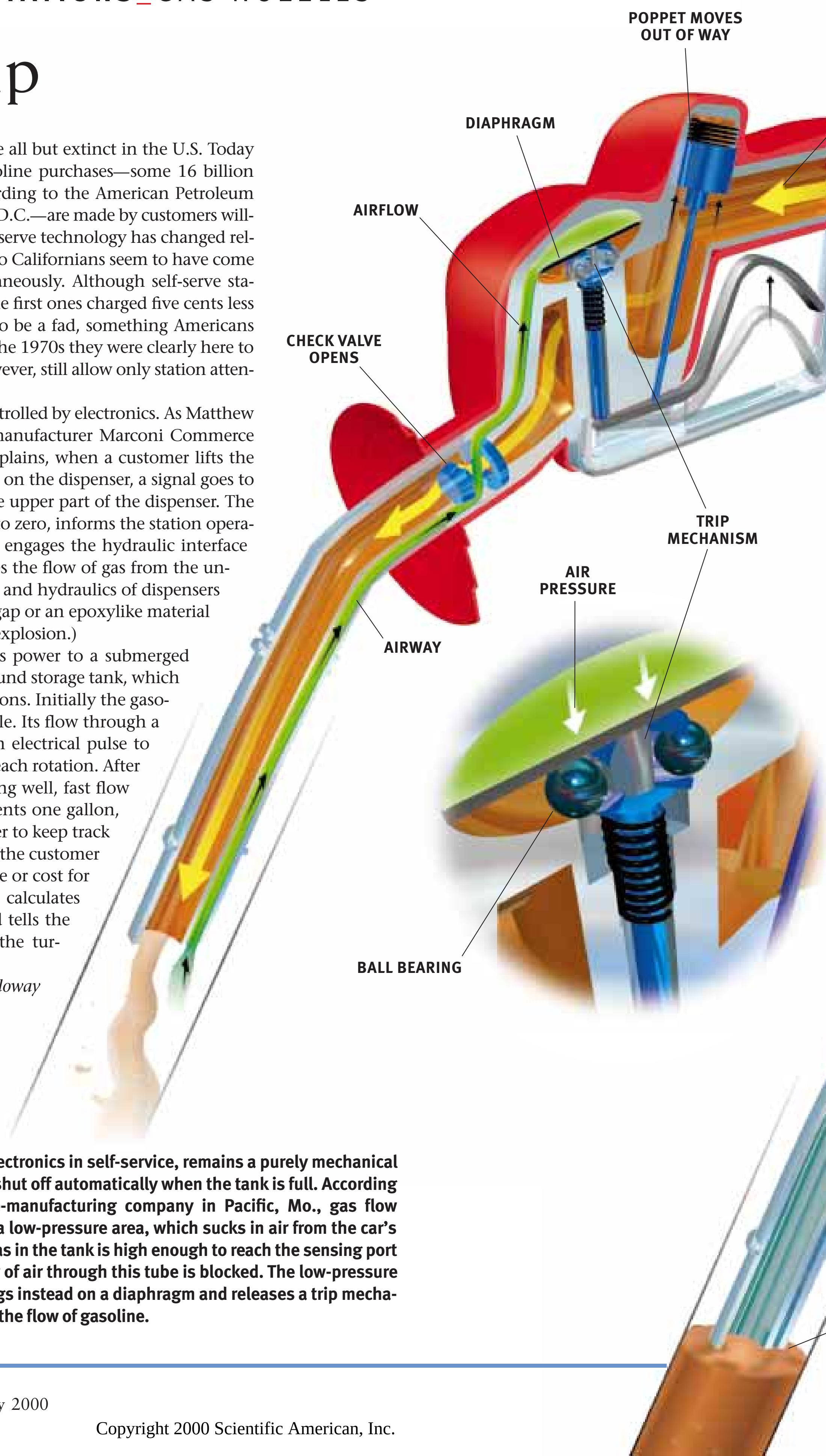
Fill 'Er Up

Full-service gas stations are all but extinct in the U.S. Today about 90 percent of gasoline purchases—some 16 billion transactions a year, according to the American Petroleum Institute in Washington, D.C.—are made by customers willing to pump for themselves. Self-serve technology has changed relatively little since 1947, when two Californians seem to have come up with the idea almost simultaneously. Although self-serve stations saved customers money (the first ones charged five cents less per gallon), they were thought to be a fad, something Americans would eventually tire of. But by the 1970s they were clearly here to stay. New Jersey and Oregon, however, still allow only station attendants to pump gas.

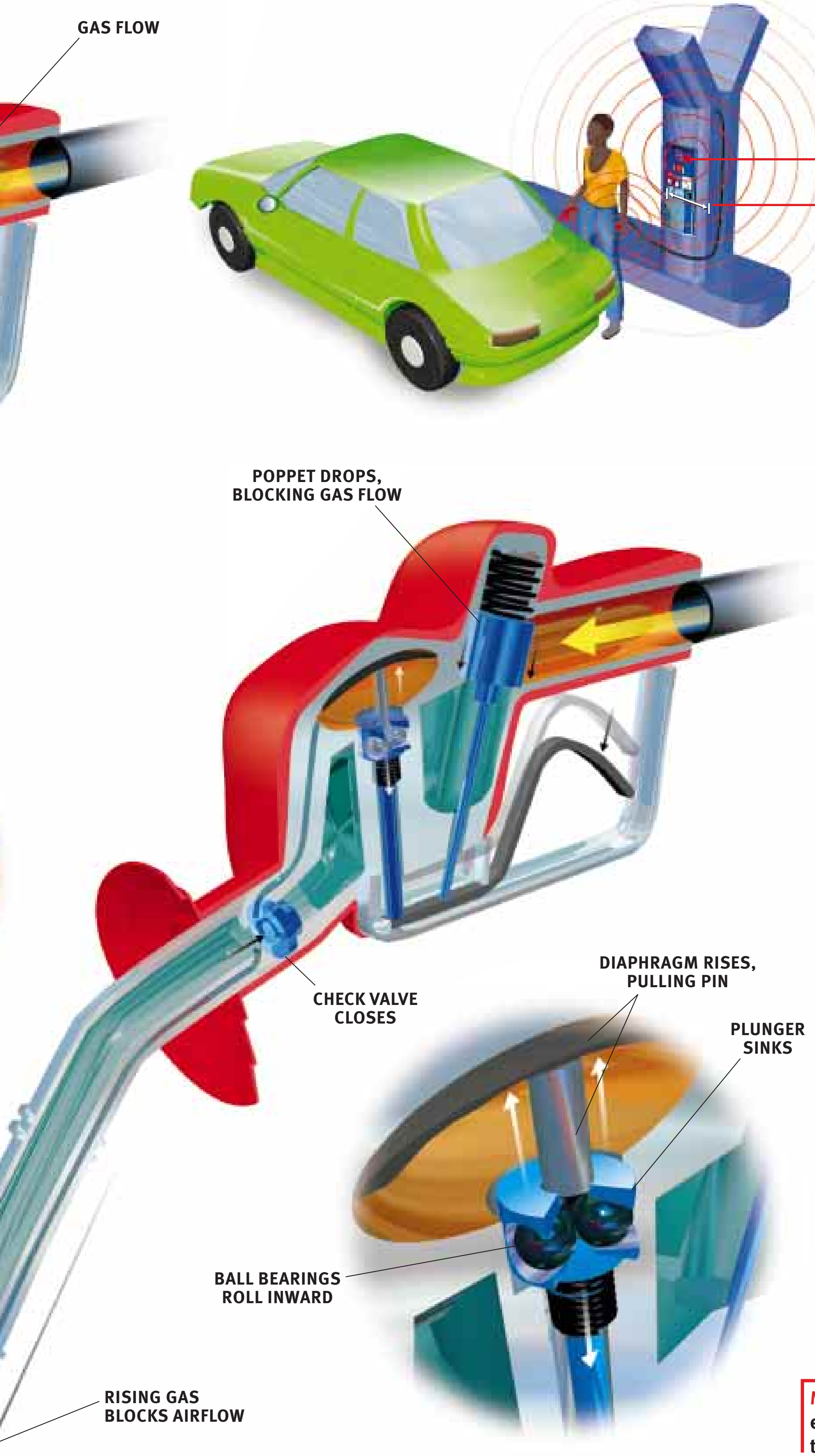
Today self-service is largely controlled by electronics. As Matthew C. Schuessler of the dispenser manufacturer Marconi Commerce Systems in Greensboro, N.C., explains, when a customer lifts the pump handle or pushes a button on the dispenser, a signal goes to the pump controller board in the upper part of the dispenser. The board resets the display counter to zero, informs the station operator that there is a customer and engages the hydraulic interface board, through which it regulates the flow of gas from the underground tank. (The electronics and hydraulics of dispensers are carefully separated by an air gap or an epoxylike material to reduce the risk of sparking an explosion.)

The hydraulic interface directs power to a submerged turbine pump atop the underground storage tank, which typically holds about 10,000 gallons. Initially the gasoline is pumped upward at a trickle. Its flow through a meter turns a disk that sends an electrical pulse to the pump controller board after each rotation. After 10 pulses, if everything is working well, fast flow starts. Every 1,000 pulses represents one gallon, which allows the pump controller to keep track of how much gas is dispensed. If the customer has specified a maximum volume or cost for the transaction, the controller calculates when this has been reached and tells the hydraulic interface to shut off the turbine, and gas flow stops.

—*Marguerite Holloway*



THE NOZZLE, despite all the electronics in self-service, remains a purely mechanical device. Nozzles are designed to shut off automatically when the tank is full. According to Husky Corporation, a nozzle-manufacturing company in Pacific, Mo., gas flow through the check valve creates a low-pressure area, which sucks in air from the car's tank through a vent tube. Once gas in the tank is high enough to reach the sensing port at the end of the nozzle, the flow of air through this tube is blocked. The low-pressure pull from the check valve then tugs instead on a diaphragm and releases a trip mechanism that drops a poppet to stop the flow of gasoline.



DID YOU KNOW ...

- Gas stations are increasingly using radio-frequency identification (RFID) so that customers can pay without using a credit card or cash. According to *National Petroleum News,* these customers have either a transmitter on the car window or a tag on a key chain. The transmitter relays a radio signal—containing identification and credit-card data—to the dispenser. In the case of the tag, it is waved in front of the dispenser, where a receiver processes the personal information.

- To help people who are pumping gas feel safer at night, some dispensers now being designed by Marconi and other companies will be shorter or thinner. The new versions, to be installed this summer, are harder for would-be attackers to hide behind.

- Despite the care taken to keep stations safe, accidental electrical sparks can trigger fires. Over the past two years, for example, at least 100 fires occurred at stations around the country, causing one death and many serious injuries, according to Robert N. Renkes of the Petroleum Equipment Institute in Tulsa. The apparent culprit in many cases is static electricity, which customers can sometimes pick up by rubbing against a car's upholstery and which can then spark when they touch the hose nozzle or tank cap. Customers should always ground themselves by touching the car before touching the dispenser or opening their tank.

- Leaks from petroleum tanks—about 400,000 in the past 10 years—are the major contaminant of groundwater in the U.S. About 380,000 of these tanks are located at service stations. Since 1998, the Environmental Protection Agency has required that these tanks be protected against corrosion and that they have hydrocarbon-sensing devices to alert owners to leaks. About 15 percent of underground storage tanks remain out of compliance, says Sammy Ng of the EPA.

MARGUERITE HOLLOWAY is a contributing editor at *SCIENTIFIC AMERICAN* and often edits the Working Knowledge column.

Working Knowledge

ILLUSTRATIONS BY BRYAN CHRISTIE, BASED ON INFORMATION FROM HUSKY CORPORATION

by Carol Ezzell, *staff writer*

Photographs by Karin Retief/Trace Images/The Image Works

Care for a Dying Continent

In Zimbabwe—where AIDS is prematurely killing a generation of adults—counselors and researchers struggle against social customs, viral resourcefulness and despair

Millicent Tigere perches expectantly on the edge of the sofa, her hands folded in the lap of her simple black skirt. At the age of 20, she has already been married for two years and has a one-year-old baby girl, now strapped to her back with a white terrycloth towel. One of her relatives died a year ago, and she suspects the cause was AIDS. She has come to the clinic today to find out if she herself has a future—or if her child is destined to become an orphan like the estimated 10 million others on the continent of Africa.

Millicent lives in a town on the outskirts of Harare, the capital city of the southern African nation of Zimbabwe. Her husband, who is 26, has a job as a bank teller—a feat, considering the country's unemployment rate of roughly 50 percent. Millicent speaks a little English, which is Zimbabwe's official language, but she prefers to conduct her AIDS counseling session primarily in Shona, her tribal tongue.

Chiratidzo Muyaka, Millicent's counselor, is a motherly figure in her 40s with glasses and big brown eyes. Her past experience as a schoolteacher shows as she guides Millicent through the "pretest" questionnaire that will prepare her for her blood test for the human immunodeficiency virus (HIV), the cause of AIDS.

Does she know how the AIDS virus is spread? Millicent confidently and correctly identifies unprotected sex, sharing hypodermic needles and childbirth as the major means through which HIV is transmitted.

Has she had sex with anyone other than her husband? She shakes her head no. Has her husband had sex with other women? "I don't think so," she answers, laughing nervously behind her hand.

Has she thought about what might happen if she tests positive? Her smile fades. She pauses to reach back and pull up one of her sleeping baby's flower-patterned socks before answering. "I get worried if I am positive, because I would be divorced [by my husband], and I worry about breast-feeding." Nevertheless, she declares, she plans to share the results of her test with her husband.

Although she says she and her husband have never used condoms because she takes birth-control pills, Millicent agrees to discuss condom use with him before she returns in two weeks to receive the results of her HIV test. She takes a dozen free condoms because, she says, she and her spouse have sex nearly every night. Then she leaves the counseling room for the clinic's examining room to have her blood sample drawn.

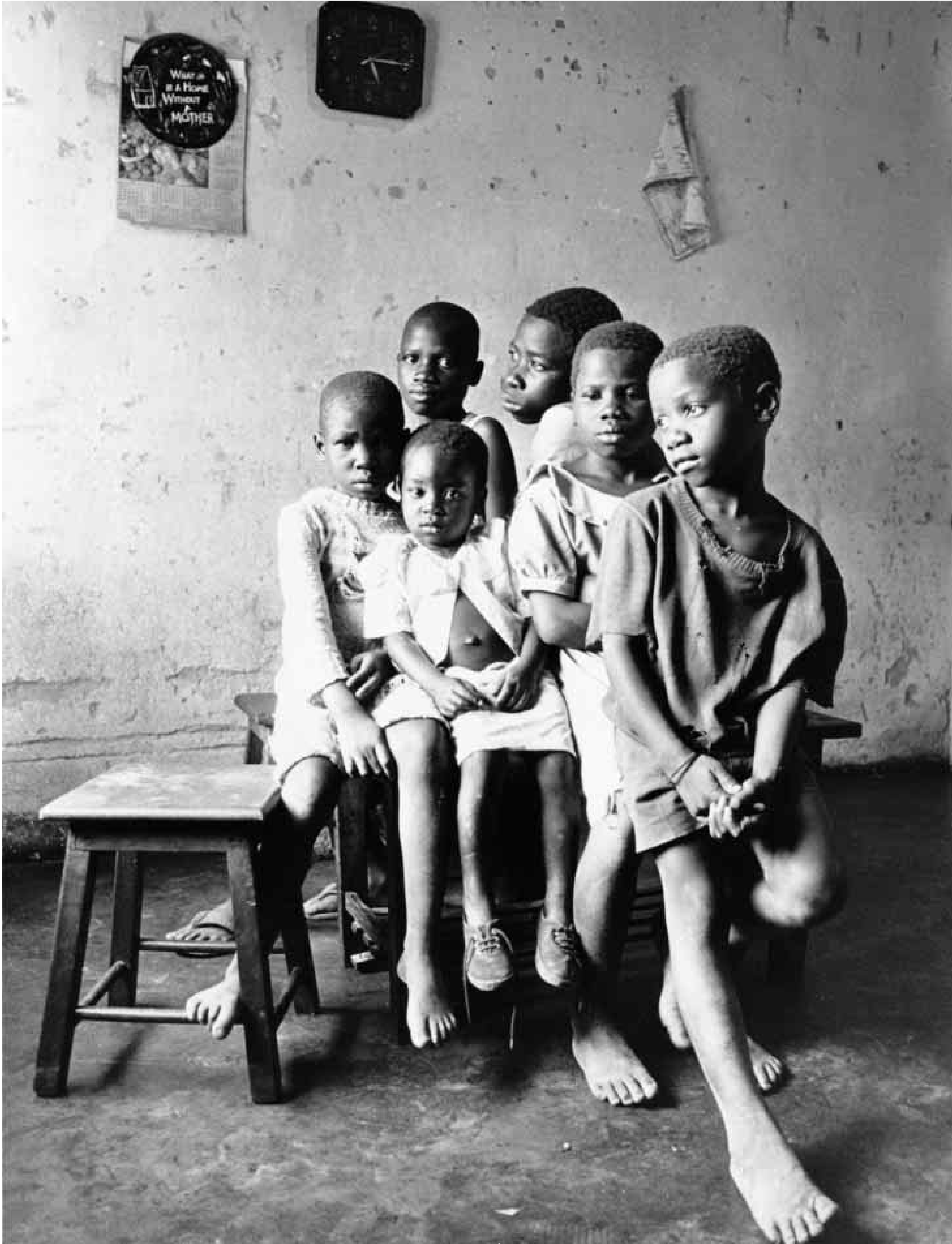
The chances that Millicent is not already infected with HIV are not good. Zimbabwe's National AIDS Coordination Program (NACP) estimates that between 20 and 25 percent of the population carries the virus. The likelihood that one in every four people I meet is infected with HIV haunts me as I walk the streets of Harare. The face of HIV is everywhere: on the taxi driver who drove me to my first appointment this morning, on my waiter last night, on the woman selling roasted corn on the cob at the side of the road, on the businessman emerging from his Mercedes.

I have come to Zimbabwe because it represents one of the best of the worst. As in other sub-Saharan African nations, the AIDS problem here is so severe that it eclipses the often-used term "crisis." AIDS is destined to alter history in Africa—and, in fact, the world—to a degree not seen in humanity's past since the Black Death. But unlike some other African countries, Zimbabwe is not riven by tribal violence. If any behavioral intervention against AIDS will work in Africa, one of its best chances will be here.

But that one-in-four estimate of Zimbabweans infected with HIV is likely to be optimistic, based on scanty data and wishful thinking. The statistic derives from blood samples collected periodically from pregnant women who show up at a dozen maternity clinics around the country—a system that even Evaristo Marowa, director of the NACP, acknowledges is inaccurate.

Workers at the clinic to which Millicent has come see HIV infection rates

THE GOMBEDZAS are one of 107 families of orphaned children who live in a single township within Marondera, a town of roughly 50,000 people that is 75 kilometers (47 miles) from Zimbabwe's capital city of Harare. Both parents died of AIDS; their grandmother, who took care of them after their parents' deaths, also died recently. They are now living in a house with no water and no electricity under the care of a 30-year-old unmarried aunt who has a three-year-old girl of her own and no job. The orphan population in Zimbabwe—a southern African nation with a population approximately that of Pennsylvania (12 million)—is growing by 60,000 each year, according to Sue Parry of the Farm Orphan Support Trust. At that rate, she estimates, the country will have 1.1 million orphans by 2005. The situation is similarly dire throughout much of the rest of Africa, which means that nearly an entire generation is growing up without parents.


WHAT IS A HOME WITHOUT A MOTHER

that are much higher. Nearly 40 percent of the women presenting themselves for HIV counseling and testing have turned up positive, according to epidemiologist Nancy S. Padian of the University of California at San Francisco. Padian is collaborating with Z. Michael Chirenje, Tsungai Chipato and Michael T. Mbizvo of the University of Zimbabwe's department of obstetrics and gynecology on studies to find ways to prevent the spread of HIV, which in Africa is transmitted largely through heterosexual sex and from mother to newborn. Like many other AIDS researchers, they are focusing on women instead of men in part because women are familiar with attending clinics during pregnancy and to obtain birth control. Their research targets reproductive-age women who are not yet infected; their goal is to keep the women and their families that way.

Because volunteers for the trials—who will number more than 10,000—must be screened for HIV, the researchers are also gathering some of the most reliable data on the true incidence of HIV infection in Zimbabwe, which is thought to be typical of southern Africa.

But for many women it is already too late. The particulars of each who comes to the clinic are recorded in a large ledger. When the results of the confidential HIV tests come back, the negative ones are entered in black ink and the positive ones in red. On many of the ledger's pages, the red ink overwhelms the black.

In the Society of AIDS

If HIV were a thinking creature capable of designing the optimum conditions in which to thrive, it couldn't have devised a better situation than Zimbabwe—and, indeed, most of Africa. Leaving aside the poverty and lack of general medical care caused by rampant inflation and joblessness, Zimbabwean culture has other vulnerabilities that HIV can exploit. First, it is a male-dominated society with a history of polygamy, where even today the characters of popular comic strips make jokes about which wife they might be staying with on a given night. Second, as in many other African countries, many Zimbabwean men come to the cities to find work, leaving their wives and children in the rural areas to which they will return only two or three times per month, according to Chiedza Musengezi, director of the Women and AIDS Support Network (WASN). While in the city, men sometimes visit prostitutes or have girlfriends, each of whom might have several men contributing to her upkeep: one who pays the rent, one who buys groceries and so on. And some of the wives left behind occasionally sell sex, too, especially right before their children's school fees come due.

During a ride through Harare one day, Rudolph, a taxi driver with a wife and seven children in one of the rural areas, tells me that most of his friends have girlfriends or so-called customary wives in town. "Some say the best thing is to [have other women and] use condoms," he says. But Rudolph, who declines to give his surname, has had a brother, a niece and a nephew die of AIDS. "I don't want to deal with other women; I just stick to my wife only," he says. "If it has been a long time, I go to see my wife. I like to control myself and have my wife take the duty [of sex]."

It is hard to tell whether people like Rudolph and Millicent are even telling the truth; people everywhere sometimes lie about their sexual behavior. When I ask Prisca Nyamapfeni—the nurse who manages the clinic where the studies headed by Chirenje, Chipato and Padian are run—whether they see many prostitutes or girlfriends, she answers that it's hard to tell. "Girlfriend" relationships can last for years, and the women usually call themselves wives. And no woman is likely to admit freely that she sells sex when desperate for money, according to Nyamapfeni. "All women say they have had one [sex] partner in the last three months," she remarks.

Sexual and hygienic practices in southern Africa also contribute to the high rate of infection. It is not uncommon for women to use their fingers, cloth, paper or cotton wool to swab the vaginal walls immediately before and during intercourse to achieve so-called dry sex,

SIX-YEAR-OLD Walter Mutsamba spends the final days of his young life at the 16-bed AIDS hospice of the Harare-based organization Mashambanzou, which loosely translates as "dawn of a new day," or more literally, "when the elephants go down to the river to drink and wash." Walter's mother and father died of AIDS in 1997 and 1998, respectively. Mashambanzou, which is operated by Catholic nuns, had 159 patients of all ages in 1998. "Helping people to die with dignity, it is so important," Sister Margaret McAllen says.

AIDS is destined to alter history in Africa—and, in fact, the world—

WAREHOUSE stacked floor to ceiling with cases of male condoms holds roughly a four-month supply for the entire country, according to storekeeper Richard Sabumba (*seated*). The condoms are donated primarily by the U.K. and are distributed from this Harare repository to clinics by the Zimbabwe National Family Planning Council. But despite the condoms' availability at no cost, many men still refuse to use them.

to a degree not seen in humanity's past since the Black Death.

which is favored by many men. Some women also insert detergents and substances obtained from traditional healers—such as herbs and, rarely, soil on which a baboon has urinated—to induce an inflammatory reaction that dries, warms and tightens the vagina.

In the February issue of the *Journal of Infectious Diseases,* Janneke H.H.M. van de Wijgert—who is now at the Population Council in New York City—Chirenje, Padian and their colleagues reported that women who use such intravaginal practices were more likely than nonusers to have disrupted the normal balance of healthy bacteria in their vaginas. Such disruptions are known to make the vagina more susceptible to sexually transmitted infections. Dry sex also works in HIV's favor because it increases the likelihood that condoms will break. In addition, it causes microtears in the vaginal walls through which HIV can gain faster access to the bloodstream.

Chirenje, a charming man who chairs the department of obstetrics and gynecology, tells me it is difficult to state the proportion of women who use intravaginal practices. "They are shy to discuss it, but it is probably a quarter to a third," he suggests.

Indeed, a recent survey—called the Voices and Choices Project—of 200 HIV-positive women in Zimbabwe indicates that the percentage could be higher. The leader of the survey, Caroline Maposhere of the International Council of Women, found that 50 percent of the women she studied wash out their vaginas with soap and water before sex. Another 20 percent douche with household detergent, and 17 percent insert herbs. "They all use something," Maposhere says. I am shocked when she tells me that fully 67 percent report pain during sex. Half of those who have painful sex have a sexually transmitted disease or pelvic inflammatory disease, which can result from repeated bouts of venereal disease; the other half attribute their discomfort to being forced by their partners or to using herbs in order to achieve dry sex.

If adult women have a difficult time lowering their risk for HIV infection, it is even tougher for young women because of the "sugar daddy" phenomenon: older men with money who look to teenage girls for sex. Young women are particularly dazzled by men who have what they refer to with their friends as "the three C's": a car, a cell phone and cash. But many of them go with sugar daddies for a far more desperate reason: money given to girls by sugar daddies is sometimes an important source of family income. The men know that the girls are less likely to have had sex—and encountered HIV—than older women. Some also believe that having sex with a virgin can cure them of HIV infection or AIDS. The HIV infection rate among 15- to 20-year-old girls is five times that of boys the same age, according to WASN's Musengezi, which indicates that the young women must be getting HIV from older men.

The male condom is the best-known means of stemming the spread of HIV, but negotiating condom use is tricky for most Zimbabwean women, particularly wives. It's not just a matter of coming home with a handful of condoms and asking their husbands to use them. "If a wife comes to me with an idea, it is downsizing me," explains Eliot, a 40-year-old AIDS counselor who himself has the disease. Men "get angry," he says, because if a wife suggests something, it implies that the man should have thought of it first. Husbands also resent being asked to use condoms by a wife because they have often paid *lobola,* or a bride price, for them.

Between a Rock and a Thin Layer of Latex

So far roughly half the women who have entered the condom acceptability study being conducted by Chirenje and Padian—which is funded by the U.S. Centers for Disease Control and Prevention—have been able to get their husbands to use condoms, in part because counselors such as Muyaka work with the women to devise "scripts" that they can use to convince their partners. They even demonstrate the proper way to use a male condom on a wooden model of an erect penis that is kept under a cloth drape. But this can be a shock, because most women are not used to seeing a depiction of an aroused penis. "More than one lady has jumped back when we showed them the penis model," Lisa Loeb, project coordinator for the study, recounts to me. "They say, 'My husband doesn't look like that!' "

LABORATORY TECHNICIAN Travor Nyamurera and U.S. epidemiologist Nancy S. Padian review a ledger that lists women who have come to their Harare clinic to be tested for the human immunodeficiency virus (HIV), the cause of AIDS. They enter negative results in black and positive ones in red. The book is filled with red: close to 40 percent of the women they and their colleagues have screened are infected.

If a woman still can't convince her partner to use a male condom, on a subsequent visit to the clinic she is offered other options, such as female condoms, which she is shown how to use on a plastic dummy of a female vulva and vagina. A female condom is essentially a plastic sheath with two flexible plastic rings at either end. The smaller ring, which is at the closed end of the sheath, is inserted over the cervix so that the sheath lines the vaginal walls. The open end of the sheath and the larger ring remain outside the body.

Although the final data are not yet in, the female condom "hasn't really taken off yet as we hoped it would," comments Gertrude Khumalo-Sakutukwa, the senior social scientist for the University of California/University of Zimbabwe col-

Nearly 40 percent of the women presenting themselves for HIV

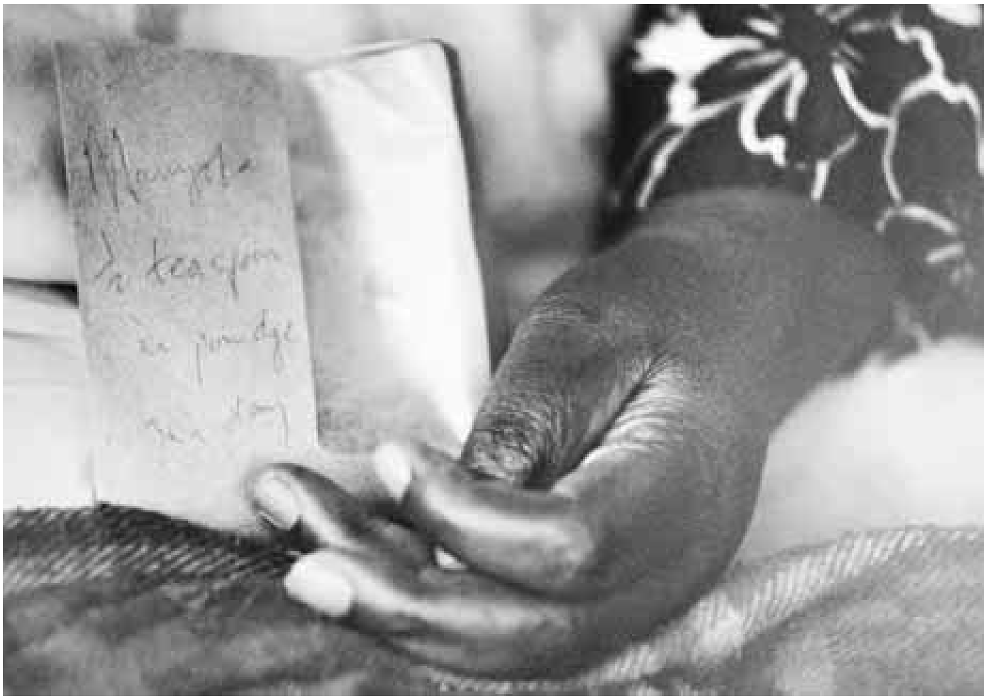
BLESSING MANDERE has come to the Harare clinic with her twin toddlers to receive an HIV test and to discuss with counselor Enedia Chitiyo how to reduce her chances of becoming infected. If she tests negative, she will be offered free condoms and continued counseling as part of a clinical trial studying the best ways to help women negotiate condom use with their partners. If she tests positive, she will be referred to local organizations for people living with HIV. But such groups, because they cannot afford antiviral drugs, usually offer clients only a sympathetic ear and advice on nutrition.

laboration. She says many women dislike the female condom, which the clinic offers free, because they claim it's ugly and unnatural and can squeak during sex.

The female condom is also expensive. The British government donates most of Zimbabwe's male condoms, which are relatively cheap to produce and can be obtained free from any clinic or for a negligible price from all kinds of shops under a subsidized marketing program. In contrast, few clinics can afford to provide free female condoms, although the aid organization Population Services International has begun underwriting a program to sell packages of two female condoms for less than 10 cents U.S.

Marowa of the National AIDS Coordination Program says that his office is "promoting both" male and female condoms. So far, though, he asserts that the male condom is more acceptable than the female one.

Whether the man or the woman wears the condom, family and sexual politics complicate the issue of condom use. If a wife asks her husband to wear a male condom, says Eliot, he might take it as an accusation of infidelity. Similarly, some men think that wives who have access to male or female condoms are more likely to sleep around. The decision to use condoms also adds another layer of complexity to the decision of when—and even whether—to have children. Mothers-in-law sometimes pressure wives to bear many children to enlarge the extended family. How can a daughter-in-law say she doesn't trust her husband enough to stop using a condom so that they can conceive?



TRADITIONAL HEALER Grace Chihyure holds an envelope containing red powdered tree bark that she recommends people with AIDS sprinkle on their porridge to control diarrhea. Chihyure says she sees 10 to 20 clients every day—most of whom have AIDS—on the porch of her modern cement house. At her feet she has a basket filled with envelopes and jars: a red root to stem weight loss, herbs to combat tuberculosis and thrush, another powder for chest pain. "It's a gift from my ancestors," she declares. "My grandmother was a great healer. She comes to me in a dream now to tell me what I am supposed to do." Lynd Francis, a U.S.-born woman who is HIV-positive and who founded a Harare AIDS support group called The Centre, estimates that 60 percent of her clients go to traditional healers for the treatment of AIDS symptoms. She says that she herself takes the tree-bark powder—which the healers call "sugar"—for diarrhea caused by HIV infection.

counseling and testing at the clinic have turned up positive.

Telling her partner that she is HIV-positive may have even more serious ramifications. Out of every 10 women who test positive, Muyaka estimates, six are initially afraid to tell their husbands. She doesn't know how many women have been dumped by their husbands. Two have come back saying they were beaten.

Offering Hope

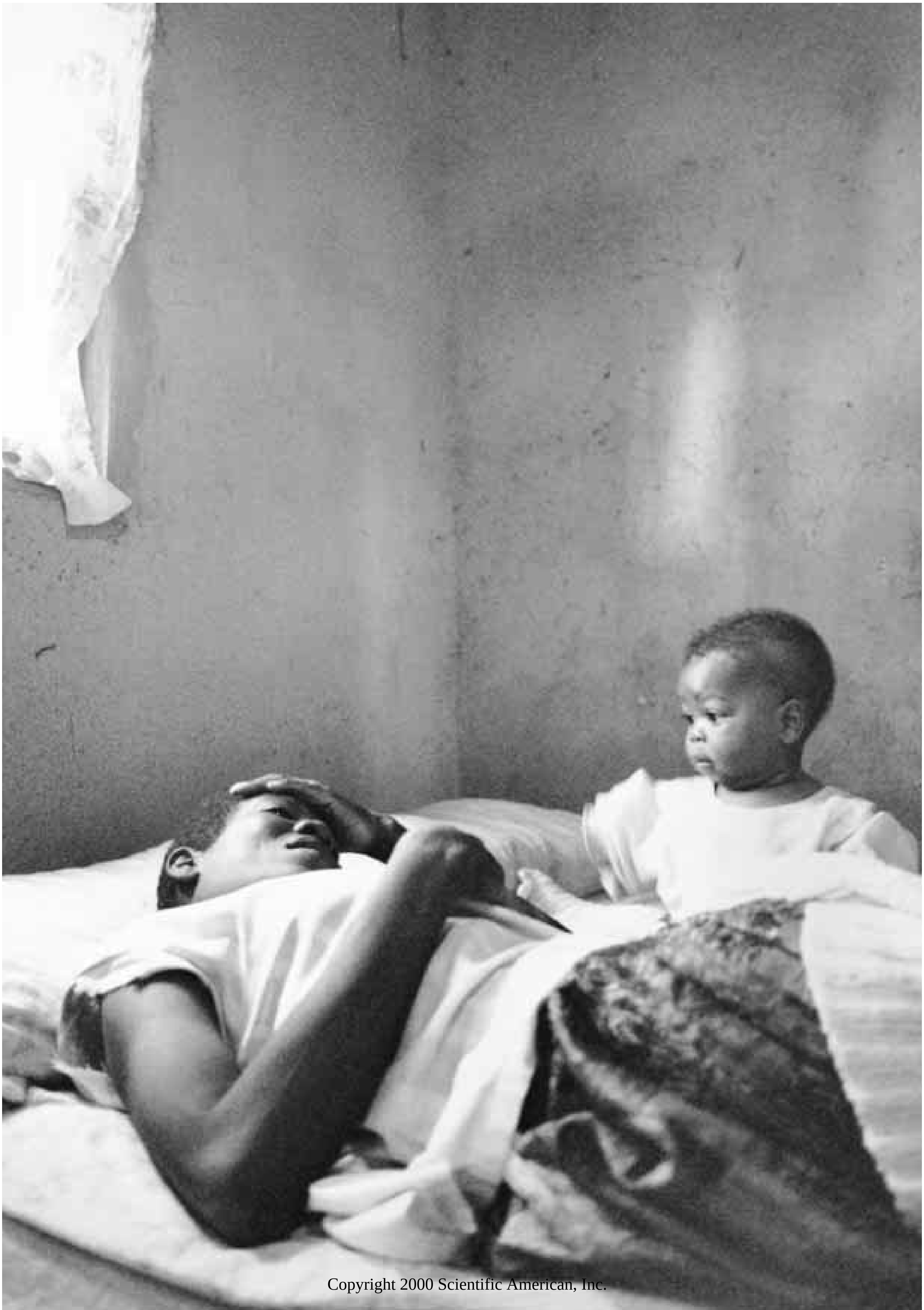
By the time our car pulls into the parking lot of the clinic on the grounds of Harare Central Hospital at 8 A.M., the women are already there: sitting in the shade of the tree or perched on the cement steps, many with babies on their backs. Most have risen before dawn and have either walked to the clinic or have taken "emergency taxis"—unlicensed minivans that are operated by men who charge the equivalent of less than one U.S. dollar to bring people into the city from the outlying "high-density suburbs," the politically correct term for the former black townships.

Our car, which belongs to the clinic's research program, isn't much better: it's an ancient Peugeot with no inside door handles and only one window handle—and even that usually bangs around like a spare tool on the dirty floorboard. To get out, we have to find the loose window handle, reattach it, roll down the window and reach out to open the door from the outside.

But all the clinic's staff are in high spirits today. Project coordinators Tinofa Mutevedzi and Joelle Brown have just found out that the preparation of nonoxynol-9 gel that they hope to offer as a backup method for protection against HIV to women who cannot consistently use condoms has been approved. And today is the first day of a dry run to work out any kinks in the procedures for a huge upcoming study of whether using hormone-based contraceptives such as the birth-control pill and Depo-Provera injections—the most popular forms of birth control in Zimbabwe—make a woman more susceptible to the AIDS virus.

Chirenje, who initially established the clinic where the AIDS studies are being conducted, is a proponent of microbicides such as the nonoxynol-9 gel, particularly for women who cannot negotiate condom use. In a previous study, Wijgert, Chirenje and their colleagues found that another preparation, called BufferGel, was "quite acceptable" to women and their partners, although some of the men at first expressed con-

Negotiating condom use is tricky for most Zimbabwean women.



cerns that the gel would lead to wet sex.

Chirenje, Chipato and Padian have high hopes for the nonoxynol-9 gel. Their gel study, which is funded by an international organization called HIVNET, will include at least 4,440 women not infected with HIV and will involve the Zimbabwe clinic as well as two clinics in the nearby country of Malawi. Women will be tested for HIV every three months for three years to see how well the gel protects them against infection.

Padian, a small, driven woman with blond hair and glasses, says she and Chipato are particularly interested in approaches that protect the cervix, which they suspect is the part of the female reproductive tract most susceptible to infection by HIV. "The study I've been wanting to do for years is to see if protecting the cervix will protect against infection," Padian declares. She is eager to do a clinical trial of diaphragms and cervical caps. "Some people think women won't use the diaphragm," she says. "But if they're willing to use the female condom, they should be willing to use a diaphragm."

She cites studies showing that diaphragms protect against chlamydia and gonorrhea, which are known to target the cervix, as well as evidence that HIV is shed more frequently from the cervix of infected women than from the vaginal walls. But she concedes that some researchers have found that women who have had complete hysterectomies, which remove the cervix, have still contracted HIV.

For now, however, the hormone study—part of a multinational HIVNET effort also involving Uganda and Thailand—will be occupying Padian's time. Project coordinators Angella Muchini and Megan Dunbar will be screening thousands of women from the Zimbabwe clinic to find 1,490 who are not infected with HIV; the total number of HIV-free women at all of the study sites will be 6,360. One third of the women will be taking oral contraceptives, one third will receive contraceptive injections, and the rest will use nonhormonal forms of contraception. All the women will be given free male condoms, which, they will be counseled, are currently the best protection against HIV. At the end of three years, researchers at all the sites will see if the women who took the hormone-based contraceptives had a higher rate of HIV infection.

This will be the first study to test the association in a statistically rigorous, straightforward manner. Exactly how hormones might make a woman more susceptible to infection is not yet clear, but the drugs are known to increase the number of epithelial cells in and near the cervix that are column-shaped. Padian speculates that HIV is better able to squeeze between the cells of the columnar epithelium than to wriggle through the layers of flat, squamous epithelial cells that line most of the vagina. In contrast, it is also possible that hormones might help protect women from HIV infection because they are known to thicken the cervical mucus, which might form a barrier to the virus.

Finding the answers to such questions may take years. In the meantime, a host of organizations are trying to change the behaviors of people in Zimbabwe, particularly those of the young. Barbara D. Chakanyuka, national youth program officer for the YWCA in Zimbabwe, runs a nationwide peer-counseling program for teenage girls. "We stress abstinence, but we also give them information on condoms," Chakanyuka says.

Lillian Savadye of the support organization AIDS Counseling Trust states that women are especially receptive to learning how to reduce their risks of infection. But learning isn't enough. "People are well informed, but the aspect of behavior change needs to be worked on," she asserts. "They know the risks, but they don't have the push to ask themselves to change their behaviors."

Why people don't do things they know are good for them is a universal conundrum, but one with deadly consequences in the wake of HIV. Nyamapfeni, the nurse who manages the Harare clinic I visited, tells me she has yet to hear of a client who says that she and her partner have ever used a male condom specifically for AIDS prevention.

Nyamapfeni, an elegant woman who favors feminine blouses and smart suits beneath her crisp white lab coat, has seen the disconnect between knowledge and behavior close to home. Her sister and brother-in-law died of AIDS a few years ago, and she and her husband and the rest of her extended family are sharing responsibility for the four orphans

THE PAUKA FAMILY—Christen, Edward and baby Sharon—cope with AIDS in their home in the rural area of Chegutu. Christen is in bed with tuberculosis, which commonly accompanies AIDS; Edward displays an itchy rash that won't heal. The Paukas are visited regularly by volunteers from an organization called Tsungirirai, which means "persevere and have courage." The group struggles with an annual budget of less than $30,000 to provide home care for 60 people with AIDS per month and to conduct AIDS education programs for the 160,000 people who live throughout the region.

left behind, aged four through 18. When I ask her what she thinks her country will look like in 20 years, she replies solemnly, “I think there are going to be very few people.” If she were in charge of Zimbabwe’s AIDS intervention efforts, she says, one of the first things she would address would be to find out why the ubiquitous AIDS education programs are having so little effect. “We are taking too long to change our behavior,” Nyamapfeni comments sadly. “We are still under a lot of denial.”

Chipato—Padian and Chirenje’s research partner—also fears for the future of his country. “Fifteen years from now it is going to be a very young population” in Zimbabwe, predicts the quiet 42-year-old with the disarming gaze. “Most of my contemporaries are dying out.”

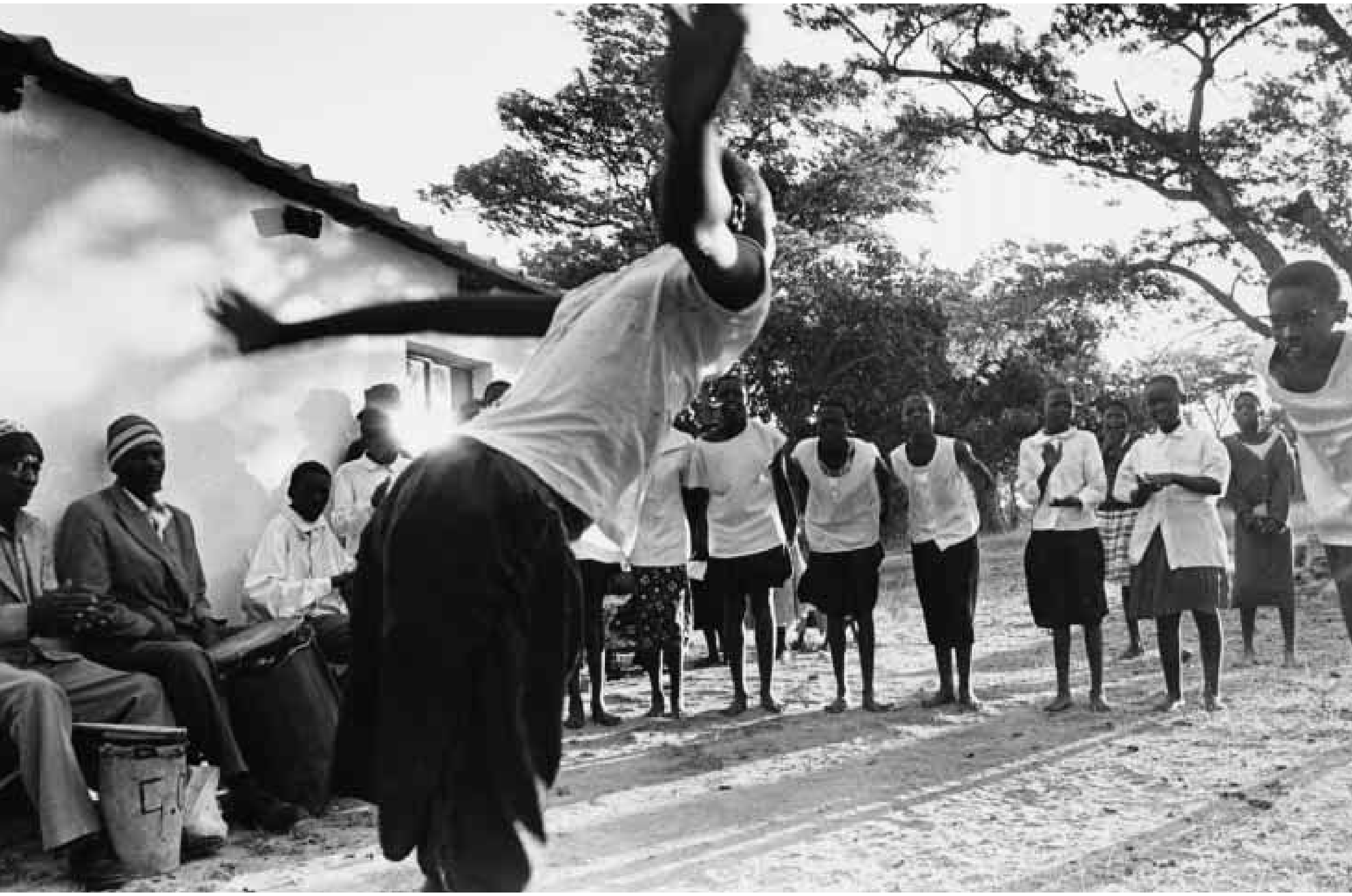
The urgency of the problem has prompted some people to propose drastic actions. Maimgehama Taderera, who leads the local chapter of an orphan organization called the Child Survival Project outside Harare, advocates rounding up all the HIV-positive people and keeping them in special villages separate from those who are not infected. Taderera knows about detainment: he was imprisoned for six years for political activities and was then under house arrest for many more years; torture by his captors left him with a limp. “If the younger generation does not change, we are going to perish,” he warns.

Others back less draconian plans. Ann Klofkorn, executive secretary of the Zimbabwe AIDS Network, applauds the recent formation by the government of a National AIDS Council to coordinate all aspects of HIV and AIDS. The current NACP is impotent, she claims, because it has purview over only the health ministry.

Helen Jackson, executive director of the Southern Africa AIDS Information Dissemination Service (SAfAIDS), agrees. “AIDS is a development issue and should be treated as such,” she asserts. Her organization also lobbied for the creation of the National AIDS Council, which so far has a budget of $8 million. “We’ve got money for the war [in the Democratic Republic of Congo, where Zimbabwe is supporting Laurent Kabila],” she says. “A lot of us would rather see the money spent on health, including AIDS [programs].”

Maposhere of the International Coun-

PROSTITUTES Mary Moyo (*standing*) and a woman who asked to be called Adelaide live and work in a ruined house without electricity or running water in downtown Harare, a short walk from a luxurious hotel frequented by foreign visitors. Adelaide, who is looking at photographs of some friends, is 32 years old and has been a prostitute for five years; Mary is 38 and has been a sex worker for 10 years. Both have children who live with relatives in the rural areas, but neither has ever been married. Prostitution is illegal in Zimbabwe, and the police regularly raid known brothels. But career prostitutes are only part of the AIDS problem: many women sell sex occasionally when their families are in need. Adelaide says that she and Mary ask their clients to use condoms but that sometimes men offer to pay them more if they will forgo using them. “From some of the symptoms we are suffering, we know we have HIV,” Mary says. “Some men could be getting HIV from us.”



GIRLS' TRADITIONAL DANCING CLUB meets in Mhondoro, one of the tribal communal lands in central Zimbabwe. The AIDS care and education organization Tsungirirai organizes such clubs to attract boys and girls to learn about AIDS. After a lesson, the children practice dancing to compete against other clubs. This group, called the Makawa Youth Club, won roughly $30, a trophy and some seed maize last year when it took first prize in a district competition. Many associations are beginning to target children as the only hope for changing some of the sexual behaviors that foster AIDS in Africa.

cil of Women sees the presidential elections in Zimbabwe, which are now scheduled for 2002, as an avenue of possible change. Robert Mugabe, who has been president since Zimbabwe's independence from Britain in 1980, has yet to declare AIDS a national emergency. "There should be more political treatment of HIV/AIDS, with resources," Maposhere contends. "If it's declared a national disaster, the money will come."

Money isn't everything, but it certainly would help. According to a report prepared in July 1998 by the NACP and the Ministry of Health and Child Welfare—of which the NACP is a part—the annual budget of the entire ministry is expected to total only $54 million this year. Marowa declined to tell me the amount of the NACP's annual budget, but he did say that only 20 percent of it derives from the Zimbabwean treasury. The rest comes from foreign agencies and donors. The U.S., for example, has spent roughly $2 million a year on AIDS-related issues in Zimbabwe since 1989, according to William B. Martin, a program officer in Zimbabwe for the U.S. Agency for International Development (USAID).

With such meager funds, the life-prolonging AIDS drugs available to many in the developed world—which cost upward of $10,000 per person per year—are unthinkable for the majority of Zimbabweans. What is left is behavior modification, which for now means condoms.

Even with its difficulties surrounding condom use, Zimbabwe seems to be the African country that has gotten the message of the importance of condom use best. Patrick L. Osewe, program director for HIV/AIDS in USAID's Zimbabwe mission, says the Zimbabwe National Family Planning Council distributes 50 million male condoms a year, "the highest number on the [African] continent."

That's roughly four condoms per year for every person in Zimbabwe. As I leave, I wonder about the outcome of Millicent's AIDS test and whether, if she tests negative, she will be one of the fortunate ones who will be able to use condoms consistently to protect themselves. Even if it is too late for Millicent, I can only hope that her daughter is uninfected and can grow up empowered enough to keep herself that way—even if she becomes an orphan. As Jackson of SAfAIDS said: "The thing that mustn't happen is saying the situation is so bad there's nothing they can do." SA

For more information on organizations mentioned in this article, visit www.sciam.com/2000/0500issue/AIDS.html

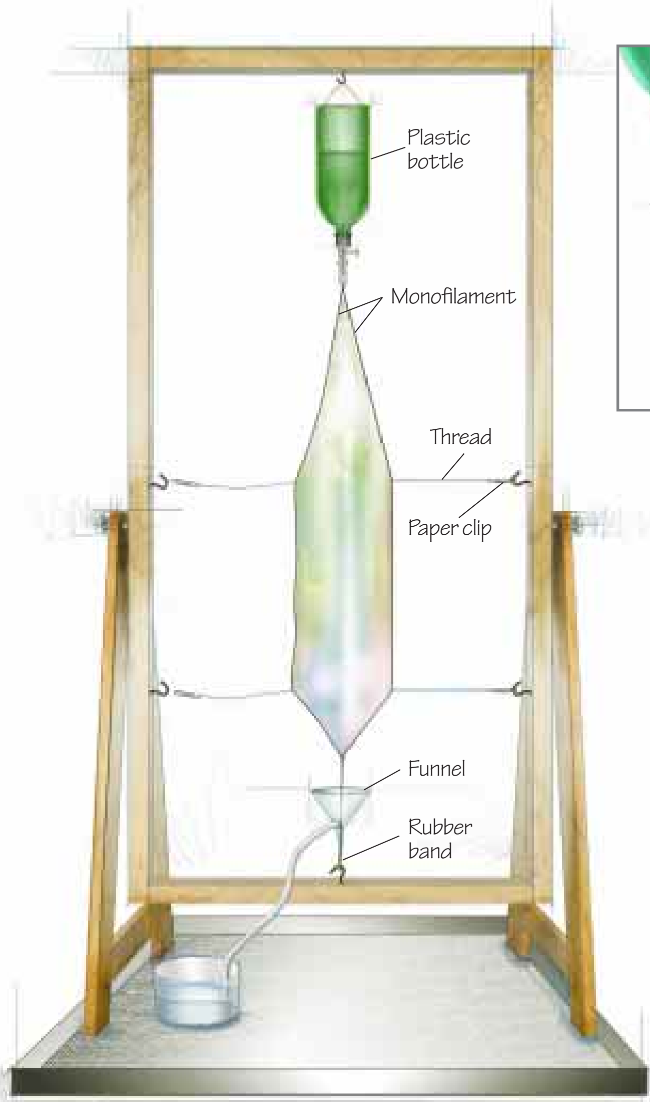
TWO-DIMENSIONAL_TURBULENCE

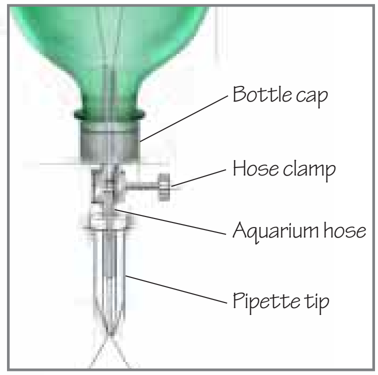
Fun with Flat Fluids

Some very serious and sober experiments with giant soap films, courtesy of **Shawn Carlson**

Maarten A. Rutgers makes soap films three stories tall. And not just for fun. Some of today's most intractable physics conundrums involve turbulent fluids. Physicists often look for ways to experiment with simpler, two-dimensional systems to check their ideas before they tackle real-world, three-dimensional problems. Rutgers, a professor at Ohio State University, has mastered 2-D fluids. So I was quite honored when he recently came to my home laboratory to teach me his secrets for making a lab-size version.

Rutgers's method is as ingenious as it is simple. He poises a reservoir of soap solution above two stretched monofilaments (single-strand string, such as 20- or 30-pound fishing line) and allows gravity to draw the solution over them. Once the filaments are thoroughly wet, he slowly separates them with four fine threads. A fast-flowing and extremely uniform soap film forms between the filaments. When he wets a small object, such as a toothpick, and pokes it into the flow, vortices form in the object's wake. The result is an awe-inspiring display of turbulent motion in two dimensions. I have now spent hours ruminating the complex interactions between patterns of vortices that I have created with toothpicks, hair combs and knife edges.





NOT YOUR STANDARD BUBBLE MAKER, this apparatus creates flat soap films. Soap solution runs out an upside-down plastic soda bottle, down along two monofilaments and into a funnel. Four horizontal threads hold the filaments apart.

A plastic two-liter soda bottle, hanging upside-down, makes an ideal reservoir for the soap [*see inset diagram at above right*]. In the bottom, cut a large hole (for refilling the solution) and two small holes (for stringing the monofilaments). The solution will drain out the bottle cap through a five-centimeter length of soft silicone tubing, which you can buy at an aquarium supply store. Drill a hole in the bottle cap with a diameter slightly greater than the inner diameter of the tube. Then cut the tip at a diagonal and thread the tube through the hole. This should create a watertight seal. If not, a dollop of aquarium cement will.

The bottle hangs from a short piece of monofilament, perhaps 30 centimeters long, strung through the small holes. A second piece of monofilament, four meters long, will guide the soap solution. Fold this piece in half, thread the two ends through the two small holes and pull them out through the tubing. At this point, you can screw the cap back on the bottle. To control the flow of solution through the tubing, attach an adjustable hose clamp, which you can find at any hardware store. To smooth out the flow as it moves onto the filament, Rutgers slides a disposable plastic pipette tip over the end of the tube, but you can also use the neck of a plastic eyedropper. You may have to trim the tip to keep the fluid flowing fast enough to maintain the film.

We hung the apparatus from a beam in my workshop, but Rutgers recommends a wooden frame that can be easily set aside for later use. The monofilaments are kept taut by a large rubber band at the bottom [*see illustration above*]. Tie the two strands together, pass them through a small plastic funnel and tie them to the rubber band. A plastic tube from the funnel drains the solution into a container. Or you could just let it drip onto a large towel or into a pan.

ALL ILLUSTRATIONS BY DANIELS & DANIELS

Last, take four thin threads about 50 centimeters long and attach a paper clip to one end of each. Tie the other ends to the monofilament. To create the film, bring the filaments together and open the hose clamp to wet them thoroughly. Then gently separate the filaments by pulling on the threads and secure the paper clips on hooks screwed into the wooden frame. This forms a film with a long straight section in which the film flows with a nearly constant speed. Opening the hose clamp increases the speed. The film will break often during your experiments, so just repeat this procedure to regenerate it.

The ideal film-making mixture is a 1 to 2 percent solution made by combining one or two parts of clear liquid dishwashing soap with 100 parts water. In English units, a 1 percent solution results from one teaspoon of soap in one pint of water. Whatever you do, avoid those bubble-blowing fluids. Gravity limits a bubble's lifetime by draining fluid away from the top until the bubble ruptures. To slow this down, toy companies add glycerin to increase the solution's viscosity. But viscosity is the last thing you need if you're studying turbulence, because high viscosity damps out turbulent motion.

The film flows between about 0.5 and 4 meters per second (1 to 9 mph)—far too fast to study the millimeter-size vortices by eye. Moreover, the turbulence can be seen only under high-contrast lighting. You'll need a strobe light or video camera with a "sports shutter" option, which limits its exposure on each video frame to between $1/1{,}000$ and $1/10{,}000$ of a second. Most new camcorders have this feature. You can also take fantastic still photographs using a fast shutter and high-speed film. Rutgers recommends ASA 3200 black-and-white film (which provides the best contrast) and a shutter speed of $1/2{,}000$ of a second or faster.

The light source must be bright enough to compensate for the quick shutter, and the best way to create high contrast is to use monochromatic light. Rutgers uses a low-pressure sodium "sox" lamp, which generates an intense band of yellow light with a wavelength of around 585 nanometers. Because essentially all the energy goes into a single wavelength, you don't need a high-wattage bulb. An 18-watt sox bulb is plenty bright and retails for about $40. Unfortunately, it requires a fixture with an electric ballast, which costs about $100. You can find such fixtures at most industrial-lighting specialty stores. To save money, check a local industrial liquidator or an on-line auction site such as eBay.com. You'll want a floodlight with a trunnion fixture that can be mounted to a tripod. If you're in the U.S., make sure the fixture is compatible with a 120-volt outlet.

As an alternative to a special lamp, Mike Rivera of the University of Pittsburgh suggests adding powdered milk to the soap solution. Place a black cloth behind the milk film and light the setup with any bright lamp. The milk film scatters more light where it is thicker, and this can provide enough contrast to show what's happening. I can show turbulence using this technique, but the re-

MAARTEN A. RUTGERS, XIAO-LUN WU AND WALTER I. GOLDBURG

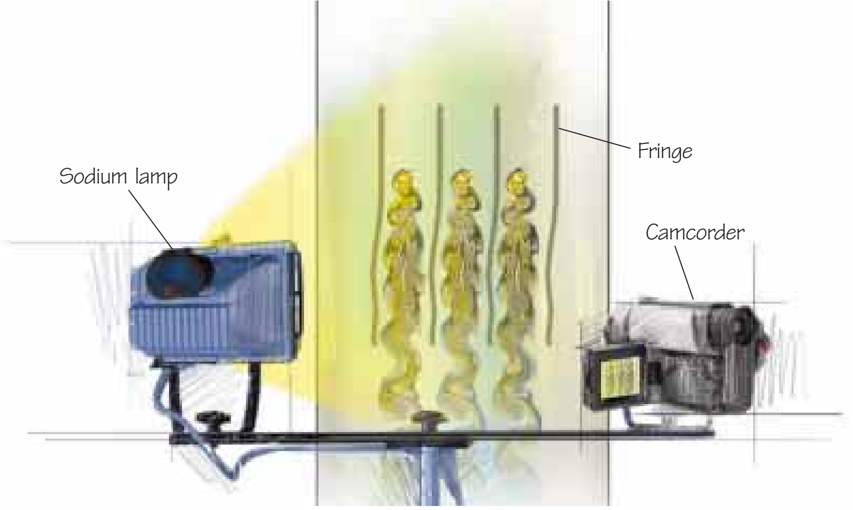
WIDENING GYRE of vortices is created by an obstacle in the soap film.

sults have not been as good as with sodium light. You may have better luck with a spoonful of white paint. Let me know what you find.

Reflected energy reaches the camera from both the front and back surfaces of the soap film. These two light trains can interfere to create fringes—widely spaced dark and light bands whose separation varies inversely with the thickness of the film. Rutgers reports that he can often get a uniformly bright surface in his laboratory, which means that the variation in film thickness is less than 100 nanometers. But the best I've been able to manage is six fringes. Turbulent flows will contort the fringes, making flow patterns visible much like smoke in a wind tunnel.

Try two simple experiments. A cylindrical obstruction, such as a toothpick, sheds pairs of oppositely rotating vortices. When two toothpicks are placed side by side, the leftmost vortex of the right toothpick interacts with the rightmost vortex of the left toothpick with a repulsive force. Can you decipher how the force between these objects changes with the separation between them? You can also experiment with shock waves. Just open the hose clamp until the flow speed is so fast that a bow shock, like the wake of a boat, appears around a toothpick. The shock wave moves toward the sides, but when it encounters fluid that is flowing too slowly, it reflects back to create a classic diamond shape.

I've enjoyed examining the flow around knife blades and through the teeth of a hair comb. And I've delighted in repeating an experiment conducted by Jun Zhang of New York University. Tie one end of a silk thread to a toothpick and let the thread whip back and forth in the flow. The motion of the thread is strikingly similar to the tail action of a swimming fish. You'll find a great many more ideas at www.physics.ohio-state.edu/~maarten on Rutgers's Web site. SA



SPECIAL PHOTOGRAPHIC SETUP, with a monochromatic light and a fast-action video camera, can take pictures like that shown on the preceding page.

For more information about this and other projects for amateur scientists, check out the Society for Amateur Scientists's Web page at sas.org and click on the "Forum" button. As a service to amateur scientists, SAS is making pipette tips available until May 2001 in packets of three for $2. You may write the society at 4735 Clairemont Square, PMB 179, San Diego, CA 92117, or call 619-239-8807.

GEOMETRY_PATTERNS

Rep-Tiling the Plane

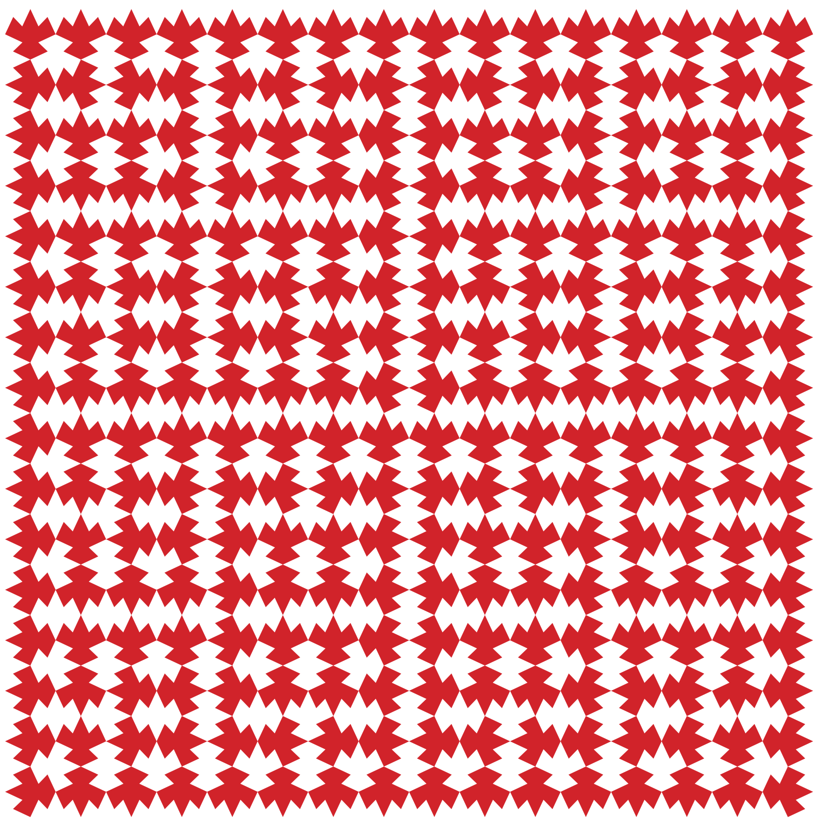
A new method makes it easy to generate intricate designs, explains **Ian Stewart**

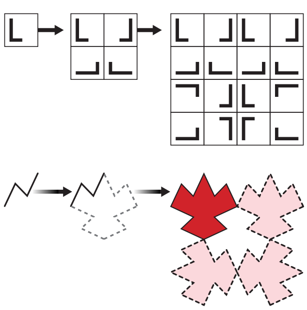
Tilings have long been a favorite topic of recreational mathematicians. The usual task is to begin with one or more fixed shapes—the tiles—and to fit them together to cover the infinite plane, or at least a large part of it. Artists have used this method to create many beautiful designs, some of which I have been pleased to present ("The Art of Elegant Tiling," Scientific American, July 1999). Not long ago a reader of this column, Michel Châtelain of Prilly, Switzerland, informed me of a completely different approach, in which the shape of the tile is pretty much the last thing to emerge. In the new procedure, we first determine how the tiles should join one another, then find out what shape of tile will do the trick.

The method is best described through examples. To begin, think of a single square. You can tile the plane with squares—as in a bathroom wall—but what we want involves, literally, a twist. The illustration below shows how to fit four squares together to make a larger square, but I've added some L shapes to show that one of the four component tiles has been translated (that is, simply slid sideways) and that the other three have been rotated or reflected (that is, the tile's orientation has been reversed, as in a mirror), or both. Rotations, reflections and translations are known collectively as transformations: they specify ways to move the square in the plane. If we repeat the same four transformations on the 4-square figure, we get the 16-square pattern shown. (The 4-square figure becomes the top left quarter of the larger square, and the rotations and reflections of the figure generate the other three quarters.)

You can apply this process repeatedly, getting arrangements of 64 squares, 256 squares and so on. Moreover, each successive arrangement becomes a part of the next one, so you can fit the entire sequence of tilings in a single infinite pattern. Depending on how you do this, the result may tile the entire plane, or some infinitely large part of it. For example, if you always fit each tiling into the top left corner of the next one, you tile an infinite quadrant—one quarter of the plane. If you fit it alternately into the top left position and the bottom right, you tile the entire plane. You might like to consider how to tile a half-plane (two adjacent quadrants).

The squares with L-shaped marks, though, are not the actual tiles we wish to create. They are merely placeholders for the tiles, showing the set of transformations that will generate the final tiling. To find a possible tile shape that will fit together according to the chosen transformations, you choose a "generator": a curve that runs from the lower left corner of the original single square to its upper right corner. (This condition ensures that the tile shape is closed.) The curve shown in





NEW TILING METHOD starts, in this example, with a 4-square figure (*top*) in which the top left square is translated (slid sideways), the top right square is reflected, the bottom left square is rotated, and the bottom right square is both rotated and reflected. The same transformations can be repeated to form a 16-square figure. If the transformations are applied to an N-shaped curve, the result is a bird-shaped tile (*above*) that fits in the same pattern (*right*).

ALL ILLUSTRATIONS BY BRYAN CHRISTIE

the illustration is an N-shaped zigzag. Now put this generator through the same four transformations that we applied to the square figures, placing the original curve in the top left corner and rotating and reflecting it to produce three joining curves.

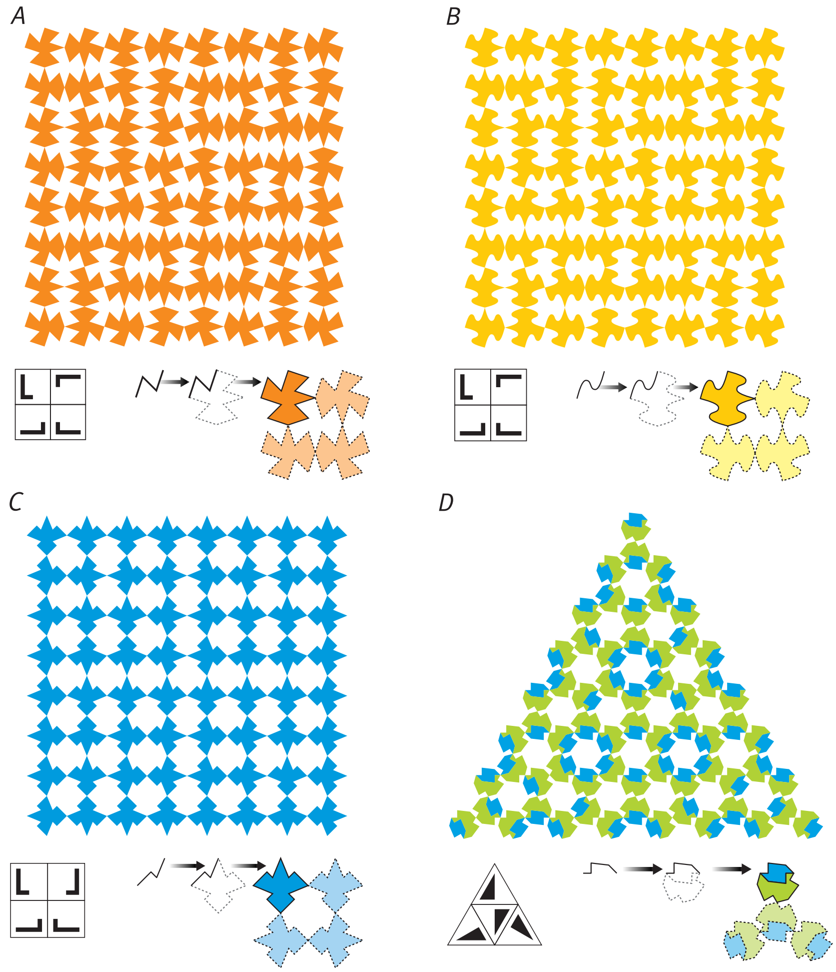
With this particular choice of generator, we get a tile shape that looks rather like a bird or maybe a human figure clad in cloak and hood. At any rate, the transformations can now be applied to this tile, just as they were to the original square, many times over. The result is a way to cover any part of the plane with infinitely many copies of this interesting tile.

The illustrations at the right show other tilings produced by the same method. If you use the N-shaped generator but a different set of four transformations, you get a different tile and pattern [*see illustration A*]. If you then change the shape of the generator, you get different tiles that fit together in the same pattern [*see illustration B*]. Note that some generators lead to more than one shape of tile [*see illustration C*].

Incidentally, the patterns that arise are usually aperiodic—they are not simple repetitions of a shape, like a wallpaper pattern. But if the set of transformations includes only translations (in other words, no rotations or reflections), you can get periodic tilings, too. Just draw a figure with four squares whose L's are all in the same orientation; any tiling produced by these transformations will be periodic.

You can also start the tiling procedure using other basic units besides a square. In fact, you can use any rep-tile—a tile shaped so that several replicas of it can be fitted together to make a larger tile of exactly the same shape. An equilateral triangle, for example, is a rep-tile—four copies fit together to make a larger one—and it can generate remarkable patterns [*see illustration D*]. Readers may be able to invent similar tilings; no one has yet managed to derive all possible rep-tiles, so there's room for fresh discoveries.

The same method also works in three dimensions: for example, eight cubes fit together to make a cube twice as big, so the cube is a replihedron. (I just made that name up. Unfortunately, it's not as clever as rep-tile.) You can even create fractal tiles—sometimes called frac-tiles—shapes that can be divided into parts that are smaller versions of the whole. The tiling procedure described by Châtelain is actually based on some of the methods used to construct fractals. It's a delightfully simple way to produce some wonderfully complex designs. SA

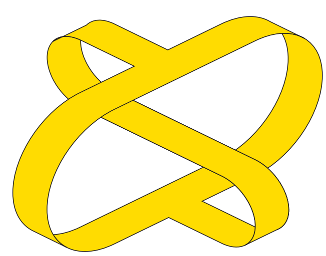


PANOPLY OF PATTERNS can be produced by changing the starting points of the tiling procedure. If different transformations are applied to the N-shaped generator, the tile and pattern will be different (*A*). If those transformations are applied to a different curve, the pattern will be the same, but the tile will be different (*B*). The method can sometimes generate more than one tile shape (*C*). One can also use equilateral triangles to specify the transformations (*D*). If the rotations shown in the 4-triangle figure are applied to the generator, it produces tiles that fit in a triangular pattern.

READER_FEEDBACK

Several recent columns have featured topological shapes. Josiah Manning of Aurora, Mo., sent me an interesting variation on the Möbius band, which is typically formed by giving a strip of paper a half-twist and then gluing its ends. The Möbius band has one side and one edge. So does Manning's shape (*below*), but at first sight it doesn't look like a normal Möbius band: the strips branch.

Topologists have learned, however, not to trust their eyes. To a topologist, a coffee cup is the same shape as a doughnut because both have one hole—in the middle of the doughnut and in the handle of the cup. Is Manning's elegant surface topologically equivalent to a Möbius band or not? If it were made of rubber, could you turn it into a typical Möbius band by stretching it, bending it or applying other continuous deformations? Bear one thing in mind: to determine equivalence, you can also cut the shape apart, as long as you rejoin the parts later so that the cut edges meet the same way they did previously. (This operation is permitted because the same topological shape may be embedded in the surrounding space in different ways.) I'll reveal the answer in a future column. —*I.S.*



REVIEWER_LORETTA DIPIETRO

Tackling Race and Sports

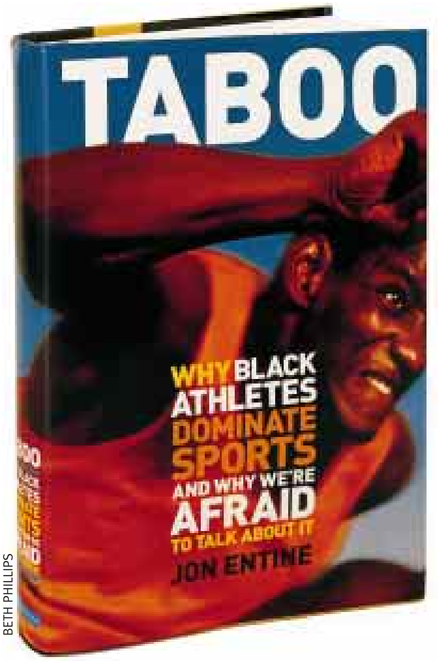
Jon Entine argues that athletes of African ancestry are better than the competition

Few issues are as provocative and as poorly understood as biological differences among the races. So loaded are statements suggesting racial superiority or inferiority that, for the most part, an anxious hush surrounds the topic. To his credit, journalist Jon Entine has tackled this problem with a no-holds-barred assault. Not shy about poking at the issue's softest spots, he goes after the history of sports and race science, the segregation and integration of sports, racial breeding and eugenics, sports and IQ, and the emergence of the black female athlete.

Entine has put together a well-researched, relatively thorough and lucidly written case, arguing that in many sports—particularly basketball, football, and track and field—athletes of African descent show a competitive advantage. He opens *Taboo* with the firm conclusion that "to the degree that it is a purely scientific debate, the evidence of black superiority in athletics is persuasive and decisively confirmed on the playing field. Elite athletes who trace most or all of their ancestry to Africa are by and large better than the competition."

While acknowledging that success in sports is a "bio-social phenomenon," he asserts that "there is extensive and persuasive research that elite black athletes have a *phenotypic* advantage—a distinctive skeletal system and musculature, metabolic structures, and other characteristics forged over tens of thousands of years of evolution. While people of African descent have spent most of their evolutionary history near to where they originated, the rest of the world's populations have had to modify their African adaptations after migrating to far different regions and climates."

Entine adds that "preliminary research suggests that different *phenotypes* are at least partially encoded in the genes—conferring *genotypic* differences, which may result in an advantage in some sports." Such differences are, of course, mediated by experience, from prenatal health to education. In other words, environment and culture can amplify or diminish tiny genetic variations. Considering the variance within each geographic, racial and ethnic population, such differences "may appear minuscule, but at the elite level, they are the stuff of champions."



BETH PHILLIPS

Taboo: Why Black Athletes Dominate Sports and Why We're Afraid to Talk about It
by Jon Entine
Public Affairs, New York, 2000 ($25)

To support this biocultural theory, Entine supplies a wealth of anecdotal information. For example, he notes that although Asians constitute 57 percent of the world's population, they make up a small fraction of professional runners, soccer players or basketball players. In contrast, whereas persons of sub-Saharan African ancestry comprise 12 percent of the world's six billion people, they disproportionately represent the top athletes in those sports requiring running, jumping and endurance.

During the 1960s, the National Basketball Association's racial breakdown stood at roughly 80 percent white and 20 percent black; today that proportion has nearly reversed. In fact, a black male has a one-in-4,000 chance of playing in the NBA, compared with a white male's one-in-90,000 chance. Meanwhile, among professional women's basketball players, 70 percent are African-American. In the National Football League, 65 percent of players are black. In college sports, 60 percent of male basketball players and nearly half of all football players are African-American. In track and field, nearly every men's world record belongs to an athlete of African descent—including the top 15 world running records (ranging from 100 meters to the marathon).

Such talent, Entine maintains, originates disproportionately in three African regions: the West African coast, North Africa and East Africa.To contrast physiological differences between populations from (or originally from) these regions and European populations, he offers descriptive data from sports anthropologists, exercise physiologists and genetic epidemiologists. Indeed, scientists have identified physical attributes that are more common to West Africans and East Africans than to Europeans, ones that might provide an edge in sprint and endurance exercises. These include a lower percentage of body fat, a higher proportion of fast-twitch muscle fibers, a greater capillary-to-muscle fiber ratio, and a superior resistance to fatigue during high-intensity endurance activities that is associated with a higher muscle oxidative capacity and with lower plasma lactate accumulation.

Entine does not examine the data on these findings closely, however. And he leaves a number of questions unanswered. Precisely how did these differences originate? The matter of temporal sequencing proves critical—that is, whether rigorous training precedes physiological adaptation (such as changes in oxidative capacity and fatigue resistance) or whether the capacity for tough training reflects a predisposing genetic endowment. Moreover, whether or not such differences are "racial" also remains unclear. And if they are racially related, do they primarily account for the dominance of black athletes in elite competitions?

Furthermore, can we generalize data on black Africans to black Americans, given that black Americans have a more diverse gene pool? For example, it is unclear whether data comparing Scandinavian and East African distance runners can be extrapolated to black and white American athletes. Another troublesome question is whether Entine's use of black individuals to support generalizations about black populations is valid—particularly if those individuals are not representative of their "race."

Thwarting Stereotypes

Despite the questions that are left hanging, Entine's emphasis on open dialogue regarding racial differences is noteworthy. He acknowledges that even to write a book about black athleticism means to probe at a wound: "Given all the controversy involved in addressing such a potentially divisive issue, it is worth asking why it even matters whether blacks are better athletes. It's a fair question and there isn't a short and simple answer. *Taboo* does its best to understand both the question and the skeptics." As such, he calls the book "self-referential," grappling with "the issue of whether it should have been written at all, considering America's troubling racial history."

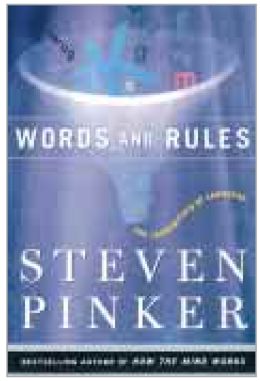
A key motivation for the book, Entine says, is to thwart stereotypes. Despite decades of social progress, "sport remains a haven for some of our most virulent stereotypes. *Taboo* is out to do some damage to these prejudices. It was written in the optimistic belief that open debate beats backroom scuttlebutt." Among the most sinister stereotypes is the notion of "the dumb jock"—the idea that athletic prowess implies lesser intelligence. *Taboo* points out that, historically, brilliant black athletic feats are often associated with "natural" talent, rather than intelligence, dedication or skill. In contrast, weak performance is associated with intrinsic black mental or moral inferiority.

To underscore his motivation for writing *Taboo,* Entine says that "the question is no longer *whether* these inquiries will continue but in what *manner* and to what *end.* Caricaturing population genetics as pseudo-science just devalues legitimate concerns about how this information will be put to use. If we do not welcome the impending onslaught of genetic and anthropological data with open minds, if we are scared to ask and to answer difficult questions, if we lose faith in science, then

THE EDITORS_RECOMMEND

STEVEN PINKER'S *Words and Rules: The Ingredients of Language.* Basic Books, New York, 1999 ($26).

"This book tries to illuminate the nature of language and mind by choosing a single phenomenon and examining it from every angle imaginable," Pinker writes. "That phenomenon is regular and irregular verbs, the bane of every language student." It is serious linguistic business that he is about, but what fun he has with it! Turning languages (mostly English) inside out, upside down and backward, he seeks to show through the way people say things something of how the mind works. Many of the speakers are children as they go about mastering their language and in so doing come up with such constructions as "I buyed a fire dog for a grillion dollars."



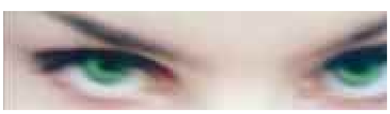
Pinker, author of the best-selling *How the Mind Works* (1997), is professor of psychology and director of the Center for Cognitive Neuroscience at the Massachusetts Institute of Technology. Musing on the "boundless expressive power" of language, he asks what the trick is behind our ability to fill one another's heads with so many different ideas. The premise of this fascinating book is that "there are two tricks, words and rules. They work by different principles, are learned and used in different ways, and may even reside in different parts of the brain." The word-and-rule theory, he says, "has solved many puzzles about the English language, and has illuminated the ways that children learn to talk, the forces that make languages diverge and the forces that make them alike, the way that language is processed in the brain, and even the nature of our concepts about things and people."

DAVID BERLINSKI'S *The Advent of the Algorithm: The Idea That Rules the World.* Harcourt, New York, 2000 ($28).

Put precisely, an algorithm "is an *effective procedure,* a way of getting something done in a finite number of discrete steps." One can also say that "an algorithm, speaking loosely, is a set of rules, a recipe, a prescription for action, a guide, a linked and controlled injunction, an adjuration, a code, an effort made to throw a complex verbal shawl over life's chattering chaos." Thus Berlinski, who has taught mathematical logic but now devotes himself to writing, introduces his deep and instructive account of the algorithm's development and its role in modern life. He does not shirk the mathematics of his subject. Although he strives to put its points clearly, the nonmathematical reader will still have to lean into them. But the same reader will find much rewarding information about mathematics, famous and not so famous mathematicians, and philosophy.

DAVID M. BUSS'S *The Dangerous Passion: Why Jealousy Is as Necessary as Love and Sex.* Free Press, New York, 2000 ($25).

Buss, a professor of psychology at the University of Texas, has spent the past decade studying "the dangerous passion of jealousy and its tethered soul mate, the specter of infidelity." Like other human passions, he says, jealousy has two sides. On the positive side, it "helped our ancestors, and most likely continues to help us today, to cope with a host of real reproductive threats." On the negative side, it "can be emotional acid that corrodes marriages, undermines self-esteem, triggers battering, and leads to the ultimate crime of murder."



FROM *THE DANGEROUS PASSION*

Men and women, Buss says, display jealousy for different reasons. To men, sexual infidelity or the suspicion of it is the trigger. To women, the trigger is emotional infidelity. Buss examines the reasons for this difference and explores other such aspects of his subject as spouse abuse, why women have affairs, and the differing sexual fantasies of men and women. He argues that jealousy has an underlying logic. "It's unlikely that love, with the tremendous psychological investment it entails, could have evolved without a defense that shielded it from the constant threat from rivals and the possibility of betrayal from a partner."

KENNETH R. MILLER'S *Finding Darwin's God: A Scientist's Search for Common Ground between God and Evolution.* Cliff Street Books (imprint of HarperCollins Publishers), New York, 1999 ($24).

Miller, professor of biology at Brown University, believes firmly in evolution. He also believes in God—a belief not widely shared among scientists. Here he sets out to offer thoughts on how to reconcile the conflict many people see between the two positions. Evolution, he says, is a story of origins; so too is the Judeo-Christian creation story. "The conflict between these two versions of our history is real, and I do not doubt for a second that it needs to be addressed. What I do not believe is that the conflict is unresolvable." Laying out the positions with care and clarity, he offers his resolution: "As more than one scientist has said, the truly remarkable thing about the world is that it actually does make sense. The parts fit, the molecules interact, the darn thing works. To people of faith, what evolution says is that nature is complete. God fashioned a material world in which truly free, truly independent beings could evolve."

GEORGE GAMOW AND RUSSELL STANNARD'S *The New World of Mr Tompkins.* Cambridge University Press, Cambridge, England, 1999 ($24.95).

Some 60 years ago physicist Gamow conceived the notion of presenting scientific ideas to the layperson through the medium of a fictional character, C.G.H. Tompkins, "a bank clerk interested in modern science." (Tompkins's initials derive from three fundamental physical constants: *c,* the velocity of light; *G,* the gravitational constant; and *h,* the quantum constant.) Gamow produced two popular books featuring Tompkins and then combined them in *Mr Tompkins in Paperback*. Now science writer Stannard presents a considerably revised version of that book. Tompkins is still a willing if rather dim learner in his associations with a physicist identified only as "the professor." Gamow and Stannard, through the professor and his daughter, Maud (who marries Tompkins in chapter 10), deal with such concepts as relativity, quantum theory and the structure of the atom. The reader will get both entertainment and plenty of information about modern physics and astrophysics.

FROM *THE NEW WORLD OF MR TOMPKINS*

ROBERT D. BALLARD'S *The Eternal Darkness: A Personal History of Deep-Sea Exploration.* With Will Hively. Princeton University Press, Princeton, N.J., 2000 ($29.95).

In 1930 two men, cramped inside a steel sphere, dipped 1,426 feet below the ocean waves and returned alive. Ever since, explorers have braved crushing pressures and icy temperatures to unveil the mysteries of the deep sea. Ballard dreamed of such adventures as a child growing up in San Diego in the 1950s, and as an adult he became an instant celebrity when his team discovered the sunken cruise ship *Titanic*. Drawing from the expertise gained during his more than 100 trips into the abyss, Ballard highlights historical and scientific events that he and Hively expertly weave into a series of scintillating tales. They tour the gamut of human emotions, from jubilation as researchers catch the first glimpse of the panoply of life thriving at a seafloor hot spring to anxiety when a submersible becomes lodged in a submarine canyon with three men trapped inside (*illustration at left*). This riveting danger has convinced Ballard that the future of deep-sea exploration should rely on remotely operated robots: "Now we can cut the ultimate tether—the one that binds our questioning intellect to vulnerable human flesh," he writes. "Through telepresence, a mind detaches itself from the body's restrictions and enters the abyss with ease."

FROM *THE ETERNAL DARKNESS*

there is no winner; we all lose." Entine uses sports, he explains, merely as a metaphor to examine why discussions of racial differences are so uncomfortable. The challenge lies in whether "we can conduct the debate so that human diversity might be cause for celebration of our individuality rather than fanning distrust. After all, in the end, for all our differences, we are far, far more similar. That's *Taboo*'s only real message."

Ironically, the greatest strength of Entine's book—its single-minded focus and clarity—likewise yields its greatest weakness. Because *Taboo* takes the form of an argument—a case to be proved, rather than an inquiry—it has a polemical flavor. Instead of sifting through fragmented, conflicting data on the rise of black athletes in sports, Entine seeks to prove his case by presuming his conclusion is true, then supporting it with selected evidence. Such a "proof" would be reasonable, were it not for his claim of reliance on the "scientific method." It is a disingenuous claim. The book does not even attempt to examine a robust data set, evaluate the strengths and weaknesses of the information, or come to an evenhanded conclusion. Instead Entine chooses to spare his readers the ambiguities of robust data, which form the core of a scientific inquiry.

> *Rather than nature* or *nurture, the answer most likely lies in an interaction between the two.*

Ultimately, the verdict is still out as to whether natural talent or hard work and determination account primarily for athletic prowess. The most probable answer is that they are inextricably linked. Rather than nature *or* nurture, the answer most likely lies in an interaction between the two. Entine's proposed biocultural theory offers an attractive explanation, suggesting that cultural conditions can amplify small but meaningful differences in performance related to heredity. Thus, inherited physiological differences may prove meaningless without rigorous training. SA

LORETTA DiPIETRO *is an associate fellow at the John B. Pierce Laboratory and an associate professor of epidemiology and public health at the Yale University School of Medicine.* *She gratefully acknowledges Nina S. Stachenfeld of the John B. Pierce Laboratory for her valuable contributions to the review.*

Wonders

Netting the Deep Sky

Philip & Phylis Morrison explain how astronomers fix the stars with amazingly fine accuracy, using units from the Babylonians

Held up at arm's length, your forefinger blocks out more than half a degree, enough to obscure the half-degree moon. No one imagines that the luminary is finger-size nor that your fist is in outer space. The match fixes neither distance nor size but only their ratio, as some fraction of a full circle. Angles have a history so long that Babylonian units are still used to describe them. In a full circle of 360 equal degrees, each degree is divided into 60 equal arc minutes, then each minute into 60 arc seconds. (We include the word "arc" with the unit to minimize confusion with the familiar measures of time.) Notice that we don't even need to know how far away the moon is to define its angular width. The length of that distant arc segment is simply proportional to its distance.

It is no surprise that astronomy and angles are old intimates. Celestial times, distances, sizes and maps largely arise from the notion of angle. The first detailed catalogue of some 1,000 star positions was reliable to about 20 arc minutes. It was made around 150 B.C. by Hipparchus of Rhodes: he probably used a tabletop brass dial. Around 1600 Tycho Brahe, with wall-size circles and metal sights without lenses, set a new accuracy record of around one minute in his list of 1,000 stars. In 1712 the first British Astronomer Royal, John Flamsteed, an ingenious pioneer of systematic telescope-aided mapping, finished his catalogue of more than 3,000 stars to an accuracy of about 10 arc seconds.

The small angular unit of one arc second is suited to the starry domain around us. Among the first fruits of the telescope was a myriad of newfound stars too faint to see by eye alone. Next came the finding that many have siblings nearby; we now count about two thirds of the stars as multiple. Close alignments of stars might be accidents of viewpoint, like sunrise over a hilltop, but real star families are crowded into a few arc seconds of sky, within which they visibly move under mutual Newtonian gravity. Then the ancient "fixed stars" in general were found to move individually relative to one another and not only in unison as the earth turns. Again, these motions across the line of sight (called proper motions) are so small that they demand relative star positions to arc-second accuracy over a few years.

Imagine a star in space. Suppose it has a large proper motion, say, five arc seconds a year. Would it simply shift its sky position slightly along a straight line? No, for the earth that carries all our telescopes around the sun every year moves in an ellipse, the form of the earth's orbit as seen from the direction of the moving star. That orbit diameter amounts to 0.4 of an arc second. The star's wobbly path seen from here records the combined effects of the proper motion relative to the sun and of the sidewise ellipse of a viewer's motion. The plot of positions raises a simple problem in surveying: find the distance to the moving star in terms of the baseline, the earth's solar orbit.

DUSAN PETRICIC

In the late 1830s the famous German astronomer and mathematician Friedrich W. Bessel made the first trigonometric distance measurement of a star—faint, fast-moving 61 Cygni at his Königsberg (now Kaliningrad) telescope. The star turns out to be about 11 light-years away. His result was low by about 20 percent from today's value (and 61 Cygni is now shown to be a triple star). In those days, star shifts were measured eye to telescope, the astronomer turning a calibrated screw to center a crosshair or to superpose split images. There is one catch. The sunlike body of even the closest star would appear as a tiny bright point only 0.02 arc second across—if imaging were perfect. Trembling, turbulent air and the limiting optics of telescopes blur all images. (Galileo noticed the effect in his first telescopic work. Stars seen with the naked eye had seemed to be arc minutes across, "crowned by twinkling rays," and even in the telescope the visual angle is "determined not by the ... body of the star but by the surrounding brilliance" experienced by the eye.)

Once photography came into the dome there was a record to work with. Stars exposed optimally are imaged as small but still blurry spots of about one arc second, often thousandths of an inch across. These can be much enlarged, the whole process well controlled, until after many exposures symmetry evens out most waywardness and the center can be determined.

After the 1950s the *General Catalogue* and a German series of particularly high quality but smaller *Fundamental Katalogs* (FK) presented distances and proper motions for thousands of stars, with errors around 200 milliarc seconds by the 1980s. Silver grains were all but replaced by electronic photon-counting devices, and the best error measures became as low as 20 milliarc seconds. That implied star dis-

Continued on page 118

Connections

What a Nerve

From Beethoven and Dickens to the chemistry of urine to "siderism"—not all science ends with a Nobel, notes **James Burke**

DAVE PAGE

In an earlier column I rashly promised to take a closer look at Beethoven's agent and the fact that the agent's granddaughter married Charles Dickens. Turns out the agent in question (a Scotsman named George Thomson) was more of an importuner. His musical forte (apart from the violin) lay in an uncanny knack for persuading great composers that the folk music he had also been collecting just wasn't up to scratch and needed improvement with attached "symphonies" or that the folk poems he'd copied down from assorted Scottish peasants needed up-to-date, catchy tunes of the new Romantic genre. Beethoven came up with over 100 such pieces, some of which were rejected by Thomson as not being good enough. Chutzpah he did not lack.

Anyway, on to Thomson's granddaughter and Dickens, who did his own share of moonlighting. In 1859, when he was already an international literary celeb for such blockbusters as *The Pickwick Papers* and *Martin Chuzzlewit*, Dickens penned a modest magazine article about a country idyll involving characters named Friar Bacon and his laborers. In real life these were, respectively, John Bennet Lawes, lord of the Manor of Rothamsted, north of London, and the people of the nearby village. Those with an organic bent will already know that Rothamsted was and is the site of the first agricultural research station, set up by Lawes in 1843 to investigate baffling bucolic matters such as why ground-up bones worked as a fertilizer in some soils but not in others. Lawes went on to make superphosphates and a fortune, together with his one-eyed chemist colleague, Joseph Henry Gilbert.

Who knew more about feeding plants than most, having spent some time with Justus von Liebig, fertilizer king, at the latter's new lab in Giessen, Germany. Where Gilbert also met (and no doubt exchanged farmyard tales with) one John Augustus Völker, himself no slouch at the midden. Apropos of which, two of Völker's more insomnia-cure papers bear special mention: "On Liquid Manure" and "The Chemistry of Silesian Sugar-Beets." Völker knew his onions (and beets, I suppose) because he had studied with the guy whom the great Liebig eclipsed. This unfortunate was Friedrich Wöhler, Liebig's lifelong shadow, friend and writer of the immortal line (to another chemistry biggie, Jöns Jacob Berzelius): "I can no longer, as it were, hold back my chemical urine." This, on the occasion when he had succeeded in synthesizing urea without the aid of a kidney. And then went on to develop a way of isolating aluminum.

The chemist's upbringing was subcontracted to a wigmaker.

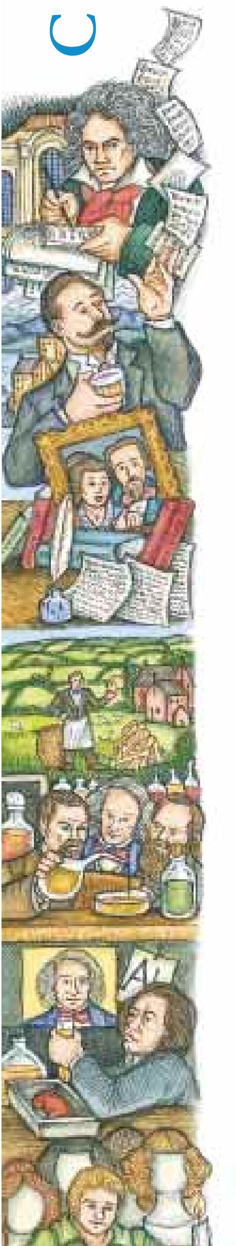
Wöhler was a chemist who was reaching spots other chemists could not. One of those others (a Dane and one of many who had failed with aluminum) suffered a fate lamentably common to children before welfare. His parents were just too busy with his siblings (mother) and work (father) to look after him and one of his brothers, so they subcontracted the boys' upbringing to an immigrant German wigmaker. Hans Christian Ørsted (the chemical boy in question) taught himself German by reading the wigmaker's Bible, then got turned on by the latest German philosophical flimflam: all that *Naturphilosophie* stuff from the Jena Romantics about how nature had evolved thanks to the resolution of opposing forces.

Thus inspired, Hans Christian went on (as some of you may know) to discover in 1819 that a live wire is surrounded by a magnetic field: electromagnetism. Interestingly enough for our present story, Ørsted had come up with a kind of early-19th-century "may the force be with you" Grand Unified Theory.

Indeed, this kind of speculative guff bumped him into a fellow whose short life (he died at 33) might best be described as "frazzled." In his 13 years of work, Johann Wilhelm Ritter (another one of those bright sparks encouraged by Alexander von Humboldt) produced a blizzard of research papers. Alas, they made no impression whatever on his contemporaries. Many of his discoveries (in electrophysiology and electrochemistry) were to be independently rediscovered by others later on. Poor old Ritter was simply in the wrong place at the wrong time. Mind you, his case wasn't helped by the fact that some of his colleagues regarded his work with much the same enthusiasm that characterizes our present views of cold fusion.

Apart from anything else, many of Ritter's results were decidedly unrepeatable, such as those from the shocking experiments he carried out on himself to find out what the effects of high voltage did to perception. Ritter was also interested in phenomena that were perhaps a little too far out on the fringe—namely, water divining, metal witching and sword swinging (not sure what these last two actually were).

To complete his ostracism from the mainstream scientific establishment, Ritter postulated a special subter-



PATRICIA J. WYNNE

ranean kind of electricity, analogous to geomagnetism. And to wrap it all together, he decided he had uncovered a general principle governing the interaction between inorganic material and human phenomena. He named this principle "siderism" and started a new journal dedicated to the matter. Folded after the first issue. Then Ritter died. Not all science ends with a Nobel.

Part of Ritter's problem might have been his guru, Franz von Baader. This was an ex-mining engineer turned mystic and ecumenicist. As a conservative Catholic, Baader's twin aims in life were to reconcile reason and revelation (you can see the appeal for Ritter) and to help unify Europe as a single community under one universal church. To which end he did what he could to foster what became the 1815 Holy Alliance of Russia, Austria and Prussia, formed after the final defeat of Napoleon and with the goal of reversing the liberal, nationalist tendencies Napoleon had stirred up everywhere. This cozy, repressive arrangement, however, went over like a lead balloon with the pope.

And with George Canning, Britain's foreign secretary, who scuppered Holy Alliance chances whenever he could. Canning was one of those brilliant intellects we used to have in politics before things became properly democratic. A dab hand at writing and an elegant speaker, at Eton he had made a lifelong friend of George Ellis, who would help found one of the great lit-crit mags of all time, the *Quarterly Review*. Through Ellis, in 1806 Canning met and became dinner-table with one of the *Review*'s more magisterial writers, Sir Walter Scott.

At the time Scott was a rising star, with his recent *The Lay of the Last Minstrel* achieving the double whammy (a succès d'estime and a moneymaker) and with his upcoming mega-best-seller *Waverley* already half-written. Scott would go on to a noble title, friendship with the king, a stately home in Scotland, and unalloyed adulation from the chattering classes of Europe and America. Exactly the kind of guy you didn't stand a chance with, if what you had in mind was asking him to knock out a few bits of doggerel to go with some old folk tunes you'd been collecting. So maybe the mention of Beethoven helped. Whatever it was, the great Sir Walter actually found time to scribble verses for the egregious George Thomson, with whom I began this piece.

Thus proving that chutzpah does it every time. SA

Wonders, *continued from page 116*

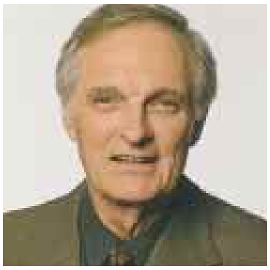
tances of a few hundred light-years, reliably inferred from new charge-coupled-device arrays of microscopic pixels.

Almost all larger celestial distances are now indirect estimates based on the surer results of geometric surveying. A 1999 review by K. J. Johnson and Christian de Vegt opens with a summary graph of that long history. The decline of angular error ran smoothly for a long time; in the 1990s it fell over a cliff as the observatory itself rose into the vacuum of space. The European space probe Hipparcos located 100,000 stars in 3-D to an overall accuracy of about one milliarc second, based on timing measurements. (This astrometric champion was the topic of our February 1998 column.)

Back in the 1950s a brand-new curve of angle error began at surprisingly high values. This work no longer refers to starlight nor even to stars. It reports on years of pinpointing quasars and radio galaxies hundreds of millions of light-years away and more, so far that they have no measurable motions across the line of sight. At eight carefully located radio telescopes spaced around North America, the Very Long Baseline Array (VLBA) stations have surveyed chosen radio sources by timing them. Narrow-band gigahertz signals received are taped at the same time with local atomic clocks, and the radio wave crests and troughs from each source at each station are centrally compared, even by the billion, to seek a best fit for relative delays and clock rate. These waves travel a foot in a nanosecond; the accuracy comes from repeatedly reading station spacings of thousands of miles to within a few feet. Some 200 sources define the radio benchmarks for the new sky map. The Hipparcos starlight positions have been painstakingly fitted into this International Celestial Reference Frame, which also incorporates the necessary earth-motion data from the decades of work on the *Katalogs*.

There is still nothing ultimate about this narrative. Ambitious plans abound for space mapping to come. Perhaps the limits will be realized at a few microarc seconds, because electromagnetic waves bend to the tiny repeated gravitational pulls of the lumpy distribution of dark and light mass as the waves thread their way to us. We will cast our nets farther and wider, but for now this VLBA/Hipparcos/FK mesh is fine. SA

PAUL SOUDERS (*photograph*); MARK A. REED (*illustration*)



Curiosity Rhymed the Cat

Alan Alda reports on readers' winning responses to his limerick challenge

Thanks to the hundreds of people who filled our mailboxes with limericks to help me understand Schrödinger and his famous feline (see the October 1999 issue). Many thoughtful and witty efforts didn't make it through the wrenching culling process, because the winning entry had to be (a) a genuine limerick (haiku, for instance, didn't count) and (b) something that would nudge this particular nonscientist farther along the road toward an understanding of Schrödinger's cat.

Thanks, too, to the phalanx of grammarians who responded to my complaint that Schrödinger's cat "would both lay there and thrive" with the reminder that chickens lay eggs, while cats lie dead. I knew that. I just find a cat that *lays there* a more amusing kind of cat.

Many contributors generously wrote accompanying essays. I found especially helpful those people who said, in effect, "Wait a minute, if the act of *observing* can decide whether something is or isn't in the quantum world, why isn't anyone pointing out that the *cat* is also an observer?" This turns out to be a very useful question. David J. Wineland and his colleagues at the National Institute of Standards and Technology have recently done experiments in which they were able to put atoms into a state that mimics that of Schrödinger's cat. Their experiments suggest that every atom can act as an observer of its neighbors (and vice versa), with the result that all probabilities, instead of cohering as a jumble of all possible states at once, decohere and fall extremely quickly into just one of those states. Therefore, Schrödinger's cat may have been perfectly capable of defending himself against quantum weirdness, and Schrödinger could have relaxed about the whole thing.

Four entries actually did turn up the wattage in my brain about poor Schrödinger's cat, and they all share first prize. They can be read almost as one continuous monologue, starting with a reference to the original argument between Bohr and Schrödinger, with a sly nod to the famous double-slit experiment in which a photon acts like both a wave and a particle (as well as to a famous cartoon by Charles Addams):

Another great Dane has made free
With a question of Be or Not Be.
Now might Schrödinger's puss,
In descending by schuss,
Leave one track on each side of a tree?

Peter J. Price

(Peter tells me that his poem was previously published by *APS News,* from the American Physical Society, so it's a two-time winner.)

The second poem takes into account the fact that Schrödinger was using the cat image in a deliberate attempt to reduce to absurdity some of the stranger notions of quantum mechanics:

Schrödinger said that a cat
Is alive, or it's dead, and that's that.
But Heisenberg said,
"It's alive *and* it's dead,
and its state can be seen as a stat."

Caleb Howard

The next entry hints at the extreme measures resorted to over the years to resolve this paradox, such as positing alternative universes:

The universe came to a junction
When Erwin collapsed his wave
  function.
He lifted the lid
And found that it hid
A pussy in need of Last Unction.

Edward Fagen

The fourth winner reflects the public's frustration over this important but arcane debate, which often involves somewhat daunting terms like the nonrelativistic quark model:

DAN WAGNER

We hardly know who we should blame
For this Schrödinger's kitty-cat game,
It gives the appearance
Of quantum coherence
And NRQM a bad name.

David J. Hall

I like to think this limerick also hints at the possible resolution of the paradox by experiments such as Wineland's. If decoherence has been reproduced in the lab and carefully measured, then we can actually watch Schrödinger's cat go from coherence, a superposition of states in which an atom can be in two places at once, to decoherence, in which the atom is confined to one place. And then maybe we can take a train from the curiously strange world of quantum mechanics to the Penn Station of our everyday world without crashing.

Finally, for those ready to abandon the whole thing because they just can't accept the idea that something exists merely because someone or something observes it, honorable mention to this one:

I'm asking you, please try to delve this,
I'm asking you, please, do not
  shelve this,
Re Schrödinger's cat
Don't you recognize that
It's quite like the status of Elvis????

Crosby Lewy

Thanks, everyone. And special thanks to those purists who contributed limericks so completely true to the form that they are totally unprintable in this magazine.

Alan Alda

Anti Gravity

MERVIN STYKES

Fields of Dreams

One jack-of-all-trades is a master of many, finds **Steve Mirsky**

Dave Baldwin might qualify as a Renaissance man, if only they had played baseball during the Renaissance. Scientific American learned of the diamond exploits of the multifaceted Baldwin when he wrote to us after our exposé of curveball aerodynamics. His letter, published in January 1998, describes how as a relief pitcher for the '69 Washington Senators, he unintentionally showed up his new manager. Pity poor Dave, as that manager was the legendary Ted Williams: Red Sox slugger, Marine captain and general misanthrope. According to Baldwin, Williams held fast to the conviction that pitchers (even his own) were "dumber than spaghetti" and challenged his staff to explain how a curveball did its twisty thing. The withering silence that greeted Baldwin's lucid curve commentary convinced Dave that pasta might indeed be his intellectual superior.

BALDWIN the strikeout artist

Other events, however, strongly indicate that Baldwin's brain works fine. He is surely the only person to publish in the *Proceedings of the Entomological Society of Washington* and to pitch for that town's team. For you younger fans, or you people who pay baseball no attention because you find it slightly less compelling than watching paint dry, Dave's Washington Senators are now the Texas Rangers, as opposed to an earlier team called the Washington Senators, now the Minnesota Twins.

Such genealogical complexity doesn't faze the former right-handed sidewinder, who went from base paths to base pairs and earned a doctorate in genetics. He also likes watching paint dry—Baldwin made it to Cooperstown when the Baseball Hall of Fame acquired one of his original works of art.

I bumped into Baldwin at the recent annual conference of the American Association for the Advancement of Science (AAAS), where he spoke during a session devoted to the science of baseball. Fellow speaker Stephen Jay Gould characterized this enterprise as "basically a guy thing rationalized as scientific and intellectual." The meeting happened to be in D.C., already lousy with ex-Senators.

The overlap between the set "major-league baseball players" and the set "holders of science-related doctorates" is as measly as a team payroll back in Baldwin's day (his maximum major-league salary was $14,000). A lone major leaguer other than Baldwin may have gone from the dugout bench to the laboratory bench: rumor has it that Lou Skizas, nicknamed "The Nervous Greek" during a few years of bouncing around the American League in the late 1950s, became a Ph.D. biologist. My attempts to contact Skizas for confirmation were unsuccessful and may have only added to his anxiety.

For every thing there is a season, but Baldwin's seasons overlapped, prolonging his Ph.D. pursuit. When he needed to be out shagging flies—*Drosophila pseudoobscura,* to be exact, for studies of genetic factors determining sex ratios—he was busy playing ball. He wrapped up his doctorate post-pitching, in 1979, to go with two previous undergraduate degrees and went on to pick up a master's in systems engineering. That last field of academe is closer to the research he presented at the AAAS: "The Decision Modeling Processes of Baseball Managers." Responses from 44 current and former big-league skippers to a questionnaire he designed led Baldwin to the conclusion that "by the book" baseball strategy has disappeared. A manager may still make an apparently traditional move, for example, bunting a runner into scoring position, but his decision is now based on mountains of data, rather than an adherence to established baseball tactics.

BY BALDWIN the scientist-artist (*Bacon's Last Experiment*)

"I think what they're doing, although they wouldn't admit this," he says, "is blame-management." That is, if a ploy fails, the manager can point to computer printouts rather than himself. The Ted Williams incident may come to mind again when he adds, "You have to understand that when you're talking to managers, there is a lot of room for misunderstanding."

His 1983 master's gave Baldwin almost as many degrees, all from the University of Arizona, as he had wins (6). He went on to perform research at his alma mater's college of agriculture, worked as an engineer and then did some molecular genetics for a small pharmaceutical company. When that temporary position ended, Baldwin devoted six years to painting, thanks to his wife's blessing and decent income. Now 62, Baldwin earns his living consulting on data-mining techniques. "I figure if I try enough things, sooner or later I'll find something I can do well," he japes. Would that all our roads curved so scenically. SA

THE TOPPS COMPANY, INC. *(left)*; DAVID G. BALDWIN *(right)*