GENETIC FUTURE OF CROPS • VIRTUAL REALITY BEATS FEAR AND PAIN

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AUGUST 2004
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DYING FOR A DRINK
Arsenic in Well Water Threatens Millions

LAWRENCE M. KRAUSS
On the Questions That Plague Physics

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Cover image by Alfred T. Kamajian.

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The Green Gene Revolution

As millions of people in Zambia and Zimbabwe faced famine in 2002, their governments rejected corn donated by the United Nations, calling it "poison" because it contained some genetically modified kernels. Similar scorn sounded this past June outside a Biotechnology Industry Organization meeting in San Francisco. There protesters blockaded the street, shouting predictions that GM crops would devastate human health, the environment and the welfare of small farmers.

PROTESTERS in San Francisco.

Yet only a month earlier the U.N. Food and Agricultural Organization (FAO)—traditionally a champion of the small farmer—had concluded that the ongoing "war of rhetoric" about agricultural biotechnology may pose a greater threat than the technology itself does. One of the worst things about GM crops, the FAO argued, is that too few farmers are planting them.

In its refreshingly apolitical report, *State of Food and Agriculture 2003–2004,* the FAO assessed a growing body of scientific and economic data on GM crops. The science, it determined, says overwhelmingly that the GM food plants currently on the market pose no risk to human health, although multiple-gene transformations now in development need further study. It also notes that more research should be done on the environmental impact of GM crops but that widespread cultivation of the plants in North and South America has so far led to no environmental catastrophes.

At the same time, the FAO pointed out that the technology's benefits could be huge for farmers in the developing world. When four million small-scale cotton farmers in China switched to planting insect-resistant GM cotton, they reaped 20 percent higher yields while using 78,000 tons less pesticide—and enjoyed a substantial drop in the annual death toll among farm workers from pesticide poisoning.

So why don't more farmers in the developing world adopt GM crops? One reason is that few are tailored to their needs. Outside China, ag-biotech research is overwhelmingly dominated by corporations, not academic centers, and the companies understandably focus their efforts on crops that deliver big profits in industrial countries, namely, corn, soy, canola and cotton. Unlike the 1960s green revolution, which was for the most part publicly funded and targeted to helping poor farmers, the gene revolution has yet to reach Third World staples such as sorghum and wheat.

European agriculture risks being left out, too, warned another study, issued in May by the European Academies Science Advisory Council. Public mistrust of GM crops has cast a pall over any plant science with the word "genetic" in its description, and state funding for agricultural research has been anemic for years. As a result, even the basic genomic studies that could improve crop traits through traditional breeding [see "Back to the Future of Cereals," by Stephen A. Goff and John M. Salmeron, on page 42] are increasingly left to corporate curiosity. But facing a political climate that is generally hostile to ag-biotech, companies have grown pessimistic about their commercial future in Europe and have begun moving their plant biotechnology divisions elsewhere.

Around the world, nations cannot keep ceding agbiotech research to big business and then complaining that corporations control it. Serious public investment by industrial countries—both at home and in the developing world, to help scientists there build their own research infrastructures—could serve both commercial and humanitarian ends. It's time to call an armistice in the war of words over ag-biotech.

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NOAH BERGER *AP Photo*

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On the Web

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FEATURED THIS MONTH

Visit **www.sciam.com/ontheweb**
to find these recent additions to the site:

Fido Found to Be Wiz with Words

Dogs may be capable of acquiring a far larger vocabulary than typical owners teach them during obedience training. Scientists experimenting with a nine-and-a-half-year-old Border collie in Germany have discovered that the dog knows more than 200 words for different objects and can learn a new word after being shown an unfamiliar item just once. The dog's ability shows that advanced word-recognition skills are present in animals other than humans and probably evolved independently of language and speech.

Record-Breaking Ice Core May Hold Key to Climate Flux

Researchers have successfully drilled through an Antarctic ice sheet to extract the longest ice core ever recovered. The cylinder of ice dates back nearly three quarters of a million years and will afford a better understanding of our planet's history of cyclical climate variation. "This has the potential to separate the human-caused impacts from the natural," comments James White of the Institute of Arctic and Alpine Research at the University of Colorado at Boulder.

Ask the Experts

How can minute quantities of chemicals such as sarin overwhelm the nervous system of an adult human so quickly?

Michael Allswede, an emergency physician and medical toxicologist at the University of Pittsburgh, explains.

COURTESY OF SUSANNE BAUS (*top*); BRITISH ANTARCTIC SURVEY (*bottom*)

IN "THE TYRANNY OF CHOICE" [April], Barry Schwartz wrote of the challenges inherent in making multitudes of decisions in a modern world. His article resonated with many letter writers. One of the choicest reactions came from Grant Ritchey of Olathe, Kan.: "On the same day I received your magazine with Schwartz's article, I purchased his book *The Paradox of Choice.* I was faced with a tough choice: Should I begin reading his book or his article? After pondering the matter carefully, I arrived at a decision with which I was satisfied. I immediately read Michael Shermer's great Skeptic column." Want to read more letters about the April issue? It's up to you.

DIFFICULT DECISIONS

I beg to differ with the assertion that the need to choose is a hallmark of modern life ["The Tyranny of Choice," by Barry Schwartz]. Our ancestors had to pick whether to rise from sleep now or later, to go to sleep here or there, and practically endless options in between. That people who have difficulties with decisions tend to be less happy can be explained by the difficulties being a result, not the cause: people with gloomier dispositions are more likely to dwell on negative thoughts, including agonizing over selections. Being a careful evaluator could actually confer an evolutionary advantage over being happy.

Gal Levin
Dallas, Tex.

Maximizers and satisficers might be emphasizing different functions: the maximizer preferring decision optimization and the satisficer stressing well-being and economy in decision making. The best coping strategy might be to employ the right mix of functions for the matter at hand. We would all want space shuttle designers to be maximizers when specifying critical life-support systems, but we might be better served by them being satisficers when they're considering whether to invest millions in a ballpoint pen that can write upside down.

Gary Myers
Spring, Tex.

My wife and I always go to Greece for our summer holiday. This year, having initially flung down the gauntlet of Cuba, I picked an island and an agent and stuck to them. Any invitation to consider anything else was met with my mantra: "I will not become a victim of the tyranny of choice!" Our holiday was booked in record time and with minimal argument. Thanks to Schwartz and all at *Scientific American* who contributed a little bit of extra happiness in our area of Suffolk.

Andrew Land
Suffolk, England

"JUST RIGHT" EVOLUTION

After reading "Evolution Encoded," by Stephen J. Freeland and Laurence D. Hurst, it occurred to me that humans could design a code with a lower error rate than that used by nature but that the lower error rate could actually be detrimental to the evolution and propagation of a species. If the error rate were too high, the species would experience dramatic mutations, resulting in swift extinction or at least a high incidence of cancer. But if the error rate were too low, natural selection would never be able to run its course, and evolution would not occur. In that case, extinction would happen just as readily as if the error rate were too high.

Perhaps nature's code has developed to have an error rate sufficient to allow evolution but not so high that catastrophic overmutation occurs. If a life-form has more or less need for evolution, its error rate, through natural selection, would be more skewed to one side or the other.

Would you please give your thoughts on this hypothesis? I am only in the 10th grade, so I realize I do not have any real expertise, but it seems (to me anyway) to make a lot of sense.

Michael Makovi
via e-mail

FREELAND REPLIES: We are merely beginning to understand the natural codes. Our recent research is testing something close to the idea you raise. An old piece of evolutionary theory (from Ronald Fisher, a statistician and geneticist whose career included stints at University College London and the University of Cambridge, writing long before life's molecular basis was known) suggests that adaptations should arise more quickly when mutations have a small effect: perhaps an "error minimizing" code is one that increases the speed at which genes adapt to changing conditions? So far the simulations elegantly support this almost paradoxical idea. I have no doubt that more surprises await discovery.

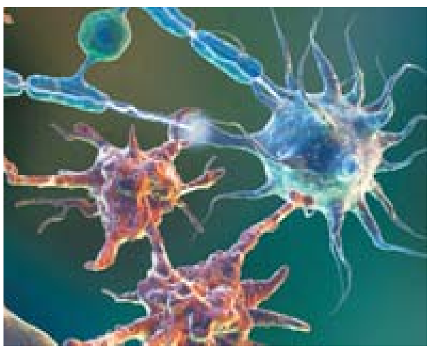
EINSTEIN'S BRAIN

In his otherwise excellent article on glial cells, "The Other Half of the Brain," R. Douglas Fields repeats a neuroscientific urban legend that Albert Einstein's brain had more glia than a "normal" person's did. This is what Marian C. Diamond et al. claimed to have shown in 1985 in *Experimental Neurology*. But, as I pointed out in that journal in 1998, their paper was "permeated with faulty methods and statistical analyses." For example, the wrong statistical test was used. Numerous different statistical analyses were performed, only one of which resulted in a significant result. Proper control brains were not used. In fact, the brains compared with Einstein's were from males who died in a V.A. Hospital. Hardly an appropriate group to compare with Einstein! Nor were the control brains matched with Einstein's on such crucial variables as age at death and time between death and autopsy. In short, the claim that Einstein's brain had more glial cells is simply wrong.

Terence Hines
Pleasantville, N.Y.

FIELDS REPLIES: In the case of Einstein's brain, we have only one. With no possibility of repeating the experiment, would it have been better not to look? After collecting the data, Diamond and her colleagues used an appropriate two-sample hypothesis test to calculate the mathematical probability that the difference in Einstein's brain might fall within the range of variation they measured in normal brains. In three regions of Einstein's cortex, their calculations showed, the glia-neuron ratios were not different enough from normal to conclude that they were clearly outside the normal range. But in an area of Einstein's brain related to higher cognitive function—including abstraction, imagery and insight—their calculations showed that there was less than a 5 percent chance that the increased number of glia could have arisen from chance variation. This is exactly what they reported.

The conclusions reached from their results are legitimate, but like all conclusions, they serve only as a new toehold to advance the upward progress of science. This is science at work.



GLIAL CELLS (*red*) have a larger than expected role in the brain.

CANOPY'S-EYE VIEW

Darren Hreniuk's attempted thievery of competing Costa Rican canopy tours by enforcing his patent, unfortunately, reminds me of similar boondoggles with intellectual-property rights in the U.S. ["Patent Enforcement," by Gary Stix; Staking Claims]. Here, of course, patent laws allow huge corporations with slick lawyers to steal basic innovative concepts by changing the color of the packaging. All convolutedly manipulated, legalistic esoterica aside, effort needs to be directed toward determining the brain in which the concept originated and assigning rights accordingly.

Ronald R. Presson
North Hollywood, Calif.

One fact has been clearly lost on Stix: Darren Hreniuk possesses an authentic, valid, government-granted patent. Period.

As *Scientific American* knows, patents are not granted on whims. Worldwide investigations are conducted to make sure proposed inventions are original, have an industrial application and do not violate other patents. It was only after a six-month investigation that Lilliana Alfaro, director of the National Registry's patent office in Costa Rica, granted Hreniuk his patent.

Yet Stix chooses to disregard expert opinion and suggests that an 1860 painting of a man crawling across a rope hand over hand and foot over foot is evidence that Hreniuk's invention is nothing but a farce. The only farce here is this lame attempt at discrediting Hreniuk's efforts. In this so-called prior-art evidence, there is no cable, no pulley, no harness, no gravitational pull and no safety. The third section of the Contentious Administrative Court in Costa Rica, when presented with this example of prior art, among other nonrelevant items, ruled that its role in this matter was over and there could be no further appeal, again verifying Hreniuk's patent.

As a legitimate patent holder, Hreniuk has the right to defend his patent. *Scientific American* choosing to mock any patent holder that has done nothing more than ask for his or her hard-earned intellectual property to be respected is reprehensible. Hreniuk's victory in Costa Rica is one to be celebrated by patent holders worldwide.

Matt Zemon
President and COO, The Original Canopy Tour
Costa Rica

ERRATUM In "Evolution Encoded," by Stephen J. Freeland and Laurence D. Hurst, the table entitled "Nature's Code" on page 87 contains a series of errors. In the bottom three blocks of the last column, all the middle-position As should be changed to Gs. A corrected table is available at www.sciam.com

JEFF JOHNSON *Hybrid Medical Animation*

50, 100 & 150 Years Ago

FROM SCIENTIFIC AMERICAN

Oppenheimer Judged ▪ Kelvin Corrected ▪ Agassiz Contradicted

AUGUST 1954

COLD WAR CASUALTY—"By a four to one vote the Atomic Energy Commission held J. Robert Oppenheimer to be a security risk and unemployable for any further atomic work in the national defense. In the Commission, dissent came from the scientist member of the jury. Henry D. Smyth asserted that Oppenheimer's continued employment would 'not endanger the common defense and security,' but on the contrary would 'continue to strengthen the United States.' His opinion presented in sharp focus the disagreement between scientists and the national administration over the present security system. The four members who condemned Oppenheimer based their decision on 'fundamental defects in his character,' and on his Communist associations, which they found 'have extended far beyond the tolerable limits of prudence and self-restraint' expected of a man in his position."

ORIGIN OF LIFE—"It is still true that with almost negligible exceptions all the organic matter we know is the product of living organisms. The almost negligible exceptions, however, are very important. It is now recognized that constant, slow production of organic molecules occurs without the agency of living things. If the origin of life is within the realm of natural phenomena, that is to imply that on other planets like the earth, life probably exists—life as we know it.—George Wald" [*Editors' note: Wald won the 1967 Nobel Prize for Physiology or Medicine.*]

FELINE DEITY—"From the foothills of the high Andes of northern Peru a river named Virú flows down a gently sloping valley into the Pacific Ocean. Only some half-buried ruins suggest its more powerful and abundant past. Pottery first appeared in the Virú Valley about 1200 B.C. At first it was a plain, undecorated ware of simple shapes; later it took on the more definite character of a culture, the central element of which seems to have been a religious cult featuring a ferocious-looking cat-god with prominently displayed incisor teeth [*see illustration*]. This demon was to haunt the cosmology of the ancient Peruvians for the next 2,000 years."

SCIENTIFIC AMERICAN

TERRIFYING CAT-GOD, an ancient funerary vessel (about 10 inches tall) from northern Peru, 1954 report

AUGUST 1904

AGE OF THE SUN—"Prof. George Howard Darwin suggests in *Nature* that previous estimates of the sun's age will have to be modified, as the result of the discovery of a new source of energy in the disintegration of the atoms of radio-active substances. Lord Kelvin's well-known estimate of 100 million years was arrived at on the assumption that the energy emitted by the sun was derived from gravitation by the concentration of its mass. Prof. Darwin estimates that if the sun were made of a radio-active material of the same strength as radium, it would be capable of emitting nearly 40 times as much energy as the gravitational energy. The multiplication of the physical estimate by 20 would bring it into very close agreement with the geological estimate."

AUGUST 1854

HUMAN FAUNA—"The paper contributed by Prof. Louis Agassiz embraces a new theory. We hope he will yet abandon such a theory, for we conceive it to be contradicted by the very facts he has presented, and is altogether unworthy of his great mind and name. The theory simply is, that man is part of the *fauna* of a country; that is, he belongs to the animals of a country, as a specific race, and that every fauna has a peculiar man race as part of it. If his theory is worth a straw, races like those which inhabit Europe ought to have been found on our continent, when it was discovered. The fauna of Canada is very like that of semi-Northern Europe. The elk, deer, bear, and beaver are natives of both continents. Yet how different is the Mohawk Indian from the Celt of Scotland, or the Scandinavian of Old Norway?"

news SCAN

CLIMATE

The Darkening Earth

LESS SUN AT THE EARTH'S SURFACE COMPLICATES CLIMATE MODELS **BY DAVID APPELL**

Much to their surprise, scientists have found that less sunlight has been reaching the earth's surface in recent decades. The sun isn't going dark; rather clouds, air pollution and aerosols are getting in the way. Researchers are learning that the phenomenon can interact with global warming in ways that had not been appreciated.

"This is something that people haven't been aware of," says Shabtai Cohen of the Institute of Soil, Water and Environmental Sciences in Bet Dagan, Israel. "And it's taken a long time to gain supporters in the scientific world." Cohen's colleague Gerald Stanhill first published his solar dimming results 15 years ago.

Estimates of the effect vary, but overall "the magnitude has surprised all of us," comments climatologist Veerabhadran Ramanathan of the University of California at San Diego. Stanhill and Cohen have pegged the solar reduction at 2.7 percent per decade over the period from 1958 to 1992. Put another way, the radiation reduction amounts to 0.5 watt per square meter per year, or about one third (in magnitude) of the warming that takes place because of carbon dioxide buildup in the atmosphere.

A separate analysis by climatologist Beate Liepert of Columbia University and her colleagues has found a 1.3 percent per decade decrease in solar radiation over the period from 1961 to 1990, with especially strong declines in North America. That's a total decline of up to 18 watts per square meter, out of the 200 watts per square meter or so that reaches the earth's surface.

Sometimes called global dimming, the reduction in solar radiation varies from region to region, and no measurements have yet been made over the world's oceans. It has also been deduced from evaporation rates around the world—the amount of water that evaporates from specially calibrated pans has been dropping for at least five decades in the Northern Hemisphere. At the May American

EARTHSHINE, the reflection of the earth on the unlit part of the moon, is one way to determine how much sunlight makes it to the surface of the earth. Brighter earthshine would suggest increasing cloudiness, which reflects sunlight away.

FRED ESPENAK *Science Photo Library*

news SCAN

NEED TO KNOW: DIM REFLECTIONS

Measurements of sunlight reaching the earth's surface, called radiometer readings, are quite variable around the world and have been tallied only up to the 1990s. An alternative reading can be had from earthshine, the reflection of the earth on the unlit part of the moon. Results from Enric Palle and his colleagues at the Big Bear Solar Observatory in California indicate a weakening of the dimming seen so far—they report a decrease in the brightness of earthshine from 1984 to 2000, suggesting fewer clouds (which block and reflect sunlight). Since 2000, however, the brightness of earthshine has been increasing, suggesting that less light is reaching the surface.

Geophysical Union meeting in Montreal, Michael Roderick and Graham Farquhar of the Australian National University presented results that extend the finding across the Southern Hemisphere as well.

A key culprit appears to be aerosols—micron-size particles (or smaller) consisting of sulfates, black and organic carbon, dust, and even sea salt. Aerosols have already been implicated in cooling tendencies, such as the slight decrease in global temperatures seen from about 1945 to 1975. Besides keeping temperatures from rising even higher than they already have, the aerosols complicate the modeling of global warming. The particulates act as the nuclei points for cloud condensation. They can lead to more cloudiness—a phenomenon called the indirect aerosol effect—which reflects sunlight away.

Solar dimming has consequences for the hydrological cycle as well. By the conventional wisdom, higher global temperatures mean that more water evaporates from the seas and falls as rain on land. But on a planet dimmed by aerosols and clouds, water vapor and rain stay in the atmosphere about half a day longer than they would in a nonaerosol world, according to Liepert's simulations. "All this debate on global warming is always discussed in terms of temperature," Liepert remarks. "I think we really have to discuss it more in terms of energy balance and water balance."

Cohen notes that the dimming effect could have consequences on farming—as a rule of thumb, agricultural productivity of light-loving plants such as peppers and tomatoes declines by 1 percent for each 1 percent decline in sunlight. Some plants, though, do better in more limited, diffuse light.

For now, scientists continue to gather data on solar dimming and puzzle through the climatological consequences. "It's going to be extremely difficult," says Ramanathan, noting the vagaries of readings. "We don't know the quality of the measurements."

David Appell is based in Newmarket, N.H.

BIOMECHANICS

Bumpy Flying

SCALLOPED FLIPPERS OF WHALES COULD RESHAPE WINGS **BY STEVEN ASHLEY**

One day in the early 1980s Frank E. Fish noticed a small statue of a humpback whale in a Boston sculpture gallery. On closer examination, he saw that the creature's large, winglike pectoral flippers were studded with evenly spaced bumps along their leading edges. Fish was taken by surprise. As a specialist in the hydrodynamics of vertebrate swimming, he knew of no cetacean flippers, fish fins or avian wings that bore such odd features—all of those have smooth front edges. He mentioned this to his wife and conjectured aloud that the artist must have made a mistake. The storeowner, overhearing Fish's comments and knowing the sculptor's meticulous attention to detail, soon produced a photograph that clearly showed the humpback's lumpy flippers. Fish marked down the unusual protuberances for future research.

LUMPY LEADING EDGES boost the hydrodynamic efficiency of humpback pectoral flippers, allowing the whale to maneuver nimbly when pursuing prey.

After intermittent study over the next two decades—involving in one instance the sawing off of three-meter-long flippers from a rotting, beached humpback—the biology professor at Pennsylvania's West Chester University and several colleagues have recently shown that the whale's knobby side appendages in some ways trump the more conventional sleek designs of both human and nature.

Working with fluid dynamics engineer Laurens E. Howle of Duke University and David S. Miklosovic and Mark M. Murray of the U.S. Naval Academy, Fish fabricated two 56-centimeter-long plastic facsimiles of humpback pectoral flippers—one with the characteristic lumps, one without. In wind-

WILLIAM W. ROSSITER *Cetacean Society International* tunnel tests at the Naval Academy, the scale model of the smooth flipper performed similarly to a standard airplane wing. The humpback flipper replica meanwhile exhibited significantly better aerodynamic efficiency.

PECTORAL FLIPPER REPLICAS, with and without bumps, went fin to fin in wind-tunnel tests.

LAURENS E. HOWLE *Duke University*

As the researchers reported in the May issue of *Physics of Fluids*, the whale's bumpy-fronted flippers generate 8 percent more lift and as much as 32 percent less drag than comparably sized smooth flippers. Further, the humpback's large, scalloped fins withstand stall at angles of attack (into the onrushing flow) 40 percent steeper than their seemingly more streamlined counterparts. "These structures are so counter to our understanding of fluid dynamics that no one had previously analyzed them," Fish says.

The key reason for the improved performance are the pairs of counterrotating swirls created at either side of the leading-edge bumps, called tubercles. "The tubercles act as vortex generators," Howle explains. "The swirling vortices inject momentum into the fluid flow, which keeps the flow attached to the upper surface rather than allowing it to separate as it would otherwise. This effect delays stall at higher angles of attack." As a result, the leviathans can make tighter turns and maneuver more nimbly—a capability that comes in handy when hunting fast-moving schools of herring and sardines.

Fish, who has patented the concept of lumpy lift surfaces, says that tests of a more accurate flipper model and functional optimization of the tubercle geometry are in the offing, which could lead to better man-made wings. Improved resistance to stall could add a new safety margin to flight and could also make aircraft more agile.

"This discovery has potential applications not only in airplane wings but also in airplane propellers, helicopter rotors and ship rudders," Howle notes. He speculates that the next America's Cup victor might tack more sharply using a bumpy rudder.

COMPUTERS

Anonymous Trust

MAKING TRUSTED COMPUTING WORK WITH PRIVACY BY WENDY M. GROSSMAN

Under pressure to battle incessant hacker attacks, viruses and identity theft, Microsoft in 2002 came up with a scheme dubbed Palladium, which would rely on special computer hardware that would refuse to run malicious programming code or betray users' secrets. A form of "trusted computing," the idea drew several objections—chief among them, it would enable remote organizations to track what users do with their machines. Now a technology based on a decade-old idea promises better-protected machines and transactions while removing the fear of monitoring.

The strategy is called direct anonymous attestation (DAA). The plan is that computers will have a secure mode in which they will run only applications that have been authenticated by remote trusted certification authorities ("attested"); moreover, these authorities would not necessarily be able identify them or their owners. A security chip on a computer motherboard or embedded in other devices would perform such gatekeeping tasks, functioning according to specifications laid down by the Trusted Computing Group, a consortium that includes Microsoft, Hewlett-Packard, Intel and IBM.

The concept behind DAA is zero-knowledge proofs, which were explored in the early 1990s at Bell Laboratories and the University of Cambridge. In zero-knowledge proofs, a person (or device) proves that he or she knows a secret without revealing it, like opening a combination lock without giving away the actual combination. Direct anonymous attestation builds on this idea and incorporates a concept from a 1991 paper by cryptographer David Chaum, who proposed a scheme whereby a group manager could digitally sign messages on behalf of group members. A message could thus be confirmed as coming from that group, but no one but the manager would know which member originated it.

Last year Jan Camenisch of IBM Research in Zurich, Liqun Chen of Hewlett-Packard and Ernie Brickell of Intel built on these ideas to create DAA. Until recently, neither the computing power nor the algorithms for implementing it were available.

For DAA to work, the secure chip, known as a trusted platform module, has a private cryptographic key embedded in it. For each group of private keys—perhaps the set of all devices of a particular model from a single manufacturer—there is a common public key. When a device needs to be authenticated as secure, it generates a new cryptographic key for one session and sends it as a message signed with its private key to a third party. The third party uses the message, the key signature and the known public key to verify the source as trusted.

The chip itself is designed to be tamperproof. Still, vendors can revoke keys if they suspect illicit activity. For instance, a DAA chip that receives multiple requests for new session keys while existing keys are still valid suggests that someone may have managed to remove the key and made thousands of hacked clones. The list of revoked keys can also be used to check that the private key be-

NOT SO TRUSTWORTHY?

In removing the fear of monitoring, direct anonymous attestation solves only one problem of so-called trusted computing. Critics such as the Electronic Frontier Foundation still worry that trusted computing can be a way for a few major manufacturers to lock out others' software or hardware, especially that of the open-source movement. Moreover, although the Trusted Computing Group insists that implementing digital-rights management systems is not part of its plan, critics fear that trusted platforms could regard users themselves as hostile attackers. In this way, the system could allow trusted remote parties to remove material from computers without their owners' consent.

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PROTECTING personal information from malevolent hackers and malicious programming code does not necessarily require an enforcement authority to know those secrets.

IMAGES.COM Corbis

ing verified is not on it. The expectation is that most verifiers will be manufacturers, but this assumption may depend on the nature of specific transactions.

These transactions can be fully anonymous, or they can be made trackable, depending on a name parameter, notes Graeme Proudler, head of the Trusted Computing Group's technical committee and a researcher in Hewlett-Packard's research lab based in Bristol, England. "At one end," he says, "the name is genuinely anonymous"—for example, if the "name" is a sequence of numbers created by a random number generator. "At the other end, it's real names, and you have a whole spectrum in the middle." He thinks such a choice is vitally important: "If it's a hospital that's accessing my medical records, then I would argue that you need a damned good audit trail, and anonymity isn't suitable."

In a climate where governments demand greater surveillance capabilities, it seems surprising that a consortium of large computer manufacturers would come up with a security chip that enables anonymity. Camenisch points to the lessons learned from Intel's 1999 announcement that all Pentium III processors would contain a unique serial number identifier. The proposal met with a public outcry. "I think the Pentium III must have changed the minds of companies and showed them that the public is really aware of such issues," Camenisch notes.

The question remaining is how successful the chips will be. Microsoft announced recently that in response to customer feedback, it is rethinking its plans for Palladium, now renamed Next-Generation Secure Computing Base. It was to be incorporated in the next version of Windows ("Longhorn"). What that will mean is still up in the air. Meanwhile Camenisch notes that IBM is working on putting the trusted platform module into its Linux systems, and he expects that the chip will become a part of many devices.

Wendy M. Grossman writes about computer issues from London.

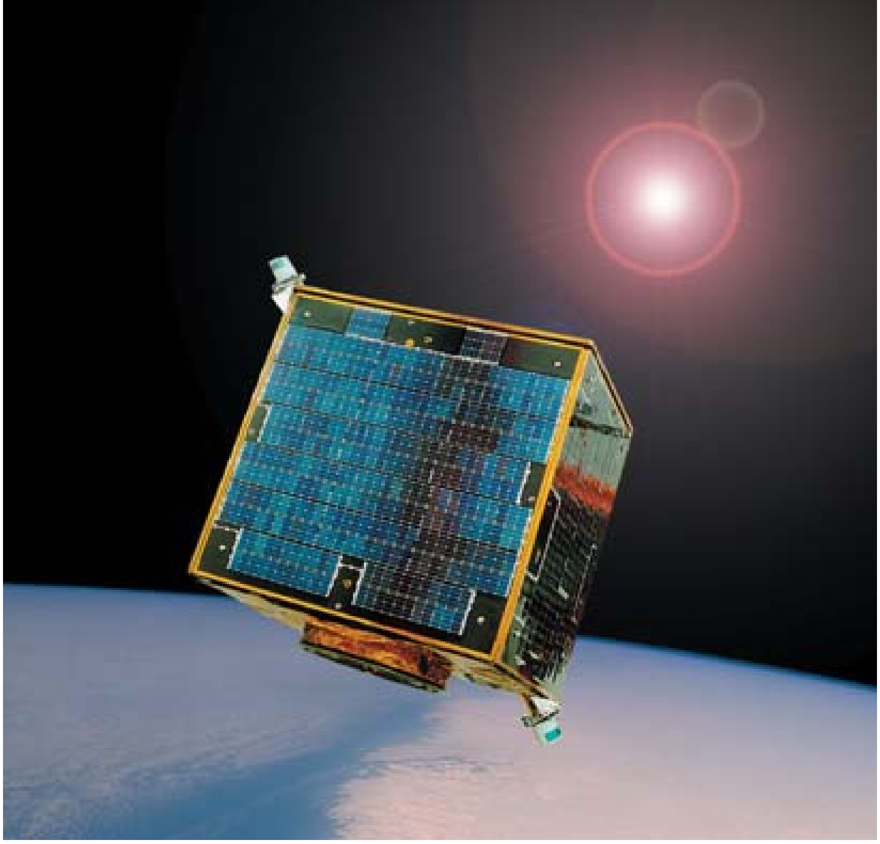
DYNAMICS

Sloshing in Space

ANALYZING HOW LIQUIDS AFFECT THE MOTION OF SHIPS BY GOVERT SCHILLING

What would you think the Dutch are launching into space this fall? Tulips? Wooden shoes? A van Gogh painting? No, it's water. The small European country that uses dikes to keep the ocean out is now sending water into Earth orbit. Carried aloft as a secondary payload by an Ariane 5 rocket in late September, the diminutive Dutch satellite Sloshsat FLEVO will study the sloshing behavior of water in weightlessness for two weeks.

Spending eight million euros ($9.6 million) to launch a couple of buckets' worth of water might seem excessive. But the work is "of international significance," states project manager Koos Prins of the Dutch National Aerospace Laboratory



NLR/ESA

SLOSHSAT FLEVO, which is 80 centimeters on a side, will help those trying to model how the motion of water, fuel and other liquids affect a spaceship's motion.

NLR. NASA's asteroid probe NEAR-Shoemaker, for instance, experienced a 13-month delay after the spacecraft unexpectedly put itself into safe mode in December 1998, possibly as a result of propellant slosh. "A better slosh model is needed for future missions," according to the report of an investigation committee. Sloshing liquid, be it propellant or drinking water, may also hamper docking maneuvers of unmanned cargo vehicles servicing the International Space Station.

Sloshsat FLEVO (Facility for Liquid Experimentation and Verification in Orbit) is a simple satellite. Basically, it is an 80-centimeter cube covered with solar cells and outfitted with small thrusters. Inside the cube is an 87-liter tank filled with 33.5 liters of ultrapure water. Heaters prevent the water from freezing. Using its thrusters, Sloshsat FLEVO is made to shake, rattle and roll. Delicate sensors on the tank walls then measure the sloshing behavior of the water, while sensitive accelerometers gauge the resulting motions of the spacecraft.

According to Sloshsat principal investigator Jan Vreeburg, a satellite with sloshing liquid is like a surfboard. "It doesn't matter that the fluid is on the inside rather than on the outside," he points out. "What's important is to understand how the motion of the liquid influences the motion and orientation of the spacecraft." Until now, Vreeburg says, spaceflight engineers have been treating their craft like surfers who lie still on their boards, just hoping that nothing ever happens. "Maybe the Sloshsat experiment will teach us how to stand up," he remarks.

Indeed, predicting, anticipating and even using the motions induced by sloshing liquids on spacecraft may someday become routine. Arthur Veldman, a computational fluid dynamicist at the University of Groningen, hopes that Sloshsat FLEVO will verify his computer models, which may then be used to gain precise control over satellite motions. "Eventually we want to develop slosh-proof space systems," he asserts.

Meanwhile the Dutch are keeping their fingers crossed. Sloshsat FLEVO is hitching a free ride on the Ariane 5 ECA. The first of this upgraded version of the European launcher exploded in December 2002. Says project manager Prins: "We circumnavigate most problems by hoping everything will work out just fine."

Govert Schilling writes about astronomy from Amersfoort, the Netherlands.

BIOTECH

Outsourcing Drug Work

PHARMACEUTICALS SHIP R&D AND CLINICAL TRIALS TO INDIA **BY GUNJAN SINHA**

Girish Virkar doesn't sleep much these days. "I've got a lot to do," he laments, as he settles into a 6 A.M. flight from Frankfurt to Milan. His mission: to drum up business for his company and cash in on the latest trend in outsourcing to India—drug research and clinical trials.

Virkar is CEO of the Mumbai-based D&O Clinical Research Organization—a firm that has been manufacturing precursor drug compounds for foreign pharmaceutical companies for more than a decade. Just this year, however, D&O expanded its services to include support for clinical trials, specifically, coordinating the studies and managing data. The expansion is intended to corral more clients as India's business climate heats up. As part of a World Trade Organization agreement that India signed in 1995, starting next year the country will honor product patents. Pharmaceutical corporations, once fearful of drug pirates, can hardly wait to move in.

MORE THAN PUSHING PILLS: Changes in India's patent laws are encouraging pharmaceutical companies to conduct research and development there as well as to hold clinical trials.

BALDEV *Corbis Sygma*

Although pharmaceutical giants such as Novartis, Pfizer and Eli Lilly have commissioned Indian firms to manufacture compounds for years, all R&D work—drug design and preclinical testing—has been done elsewhere. But during the past year, all three have publicly stated that they are actively looking at the Indian market to perform R&D services, asserts Alok Gupta, head of life sciences and biotechnology at Rabo India Finance, an investment bank. "This is a huge opportunity."

The intellectual-property law change will also jump-start growth in the market for the clinical trials, Gupta says. Since 1970 India's patent laws, which recognized processes only, did not necessitate clinical trials. Knock-off artists would study a drug released in the U.S. or Europe, manufacture it through a different process, and then sell the generic for a pittance. Today most of the 20,000 pharmaceutical companies in India make generics, Gupta states: "It has been a situation where there was no specific requirement for clinical testing, so the expertise never developed."

But as foreign companies set up shop in India, expertise will grow. Take Mumbai-based SIRO Clinpharm, one of India's first contract research organizations. It has been performing clinical trial services for the past seven years. Each year business has grown 60 to 80 percent with almost 90 percent coming from international sponsors, says general manager Chetan Tamhankar. With the change in intellectual-property laws, SIRO Clinpharm expects business to "skyrocket," he adds.

Drug outsourcing's biggest plus is cost savings. Pharmaceutical companies spend as much as 20 percent of their sales on research and development. Indian drugmakers spend a quarter as much or less. And clinical trials in India cost as little as 40 percent of those conducted in Western countries, Rabo India Finance reports.

Outsourcing is also more efficient. The German manufacturer Mucos Pharma approached SIRO Clinpharm to find 750 patients to test a drug for head and neck cancer. Within 18 months the company had recruited enough volunteers across five hospitals. In Europe, it took double the time across 22 hospitals to find just 100 volunteers.

Certainly India isn't the only country to which pharmaceutical companies can take their business. "Over the years, we've seen a large amount of data coming in from South America, eastern Europe and China," says David Lepay, senior adviser for clinical science at the U.S. Food and Drug Administration. India does, however, offer a few unique advantages. "You can speak English," notes Enzo Bombardelli, CEO of Milan-based Indena, which develops plant-derived pharmaceuticals. "In Russia and China, you need interpreters. The doctors can read English, but they have difficulties." Indian science and

OUTSOURCING GOOD AND BAD

In the political face-off over outsourcing, politicians will have to decide whether the benefits outweigh the costs. Outsourcing speeds up drug development, which is good news for the industry, its stockholders, and the medicine-using public. Indian businesses will benefit substantially: "Things are excellent," says Girish Virkar of D&O Clinical Research Organization. "We've just signed four agreements for data management and one for a clinical trial." But going global is more bad news for Westerners on the hunt for jobs. Although there haven't been mass layoffs, points out Neil Sawant of drug giant Novartis, the industry isn't hiring in the U.S.: "It won't be easy for the next generation."

medical students are taught in English.

Another plus is the country's thousands of chemists, nurtured by India's drug copycat industry. "If we give the Chinese a recipe for a compound, they can manufacture it cheaper and faster because they can put more people on it," explains Neil Sawant, associate director of purchasing at Novartis. "But we're not looking for someone to just crank the process." Novartis wants to streamline procedures and develop faster manufacturing methods, too. "Indians are very good in this area," he adds.

Gunjan Sinha is based in Frankfurt.

POLICY

A Plan for Water

A WELCOME FEDERAL STRATEGY OF OCEAN CARE HAS SOME WORRIED NONETHELESS BY ELIZABETH QUERNA

Ocean policy and management have not attracted much national attention during the past few decades, but that may be changing. A recent federal report brings together years of research and comes to the long-standing yet little heeded conclusion that the oceans are in trouble. Almost everyone, including conservationists, environmental groups, state officials and industry representatives, applauds the report for taking major steps toward improving management of the oceans. But there is still concern, especially among some U.S. states, that the recommendations will not be fully funded and that they may encourage offshore oil and gas drilling, an activity some states have fought to restrict.

The 450-page report of the U.S. Commission on Ocean Policy, a 16-member presidential committee, is the first federal study since 1969 to take a broad look at the health of the nation's oceans, and it propounds an overhaul of ocean policy. Among its proposals are a shift in wildlife management from an approach based on a single species to one based on ecosystems; the creation of a National Oceans Council within the executive branch; and a doubling of federal money allocated to ocean research, from $650 million to $1.3 billion (the amount has fallen from 7 percent of the national budget 25 years ago to just 3.5 percent today). "Given our power and enormous wealth, for us not to pay attention to our oceans is unconscionable. We have to lead by example, and we're not doing that now," says William D. Ruckelshaus, a member of the commission and a former administrator of the Environmental Protection Agency.

SEA CHANGE: A new report signals major shifts in U.S. federal policy toward managing the oceans.

The commission proposed establishing the Ocean Policy Trust Fund using money already paid to the government by offshore drilling companies that use federal waters. The trust fund, which would be worth about $5 billion annually, would go to several programs already in existence, as well as to states and to federal agencies.

But the trust fund is causing a stir among certain coastal states. Ron D. Shultz, a policy adviser to Governor Gary Locke of Washington State, worries that the money will not be appropriated. Programs that are currently funded through offshore drilling revenues, such as the Land and Water Conservation Fund, receive less money than they are promised, according to Shultz: "It's one thing to say let's have this money and another to appropriate it."

Another, possibly larger, point of contention is that the funding structure will pressure states to beef up their oil- and gas-drilling programs. The commission recommended that more money go to the states that engage in offshore energy and gas production, "because that's the source of the money, and we think the states should be compensated," explains Thomas Kitsos, the executive director of the commission.

But states that have sought to curb offshore drilling, such as those along the Pacific coast, fret that they will not receive funding unless they open their waters to more exploration for gas and oil. In California, Governor Arnold Schwarzenegger wrote in a formal comment to the commission that he supports the trust fund but "would insist that no incentives for additional offshore oil and gas development be created through the use of funds from these revenue sources."

Florida has not submitted its comments yet, but opposition there to drilling is very likely to be strong. The number of new oil and gas leases off the coast of that state has been cut by 75 percent over the past five years. In contrast, Texas and Louisiana stand to gain from the proposal. In the past 50 years, they have drilled a combined 50,000 new wells off their coasts in the Gulf of Mexico.

Despite its problems, the final report, due out at the end of the summer, is a much needed step on the way to effective ocean management. The commission hopes that its findings will be the catalyst for reform. If this study, Ruckelshaus says, "isn't a stimulation to action, I don't know what to do."

Elizabeth Querna writes about science and health from New York City.

EMILY HARRISON

OCEANS IN A SORRY STATE

The final federal report on the oceans is slated to appear at the end of the summer. It pulls together the problems found by past research, such as:

- **Pollution from runoff and industry; in 2002 fecal contamination closed more than 12,000 beaches.**
- **Development that carves up millions of acres of coastal habitats and that has brought more than 37 million people to the nation's coasts in the past 30 years.**
- **Decline of large fish such as marlin, cod and tuna by 90 percent worldwide.**
- **Collapse of major fisheries in New England and the Pacific Northwest, which has eliminated nearly 100,000 jobs.**

Middle of the Country

AS FARMING DECLINES, RURAL AMERICA ADAPTS TO SURVIVE BY RODGER DOYLE

Politically dominant until the early 1900s, rural America plunged into hard times by midcentury. Sociologists and others predicted that many areas would be depopulated and that, with improving communication and transport, urban values would overwhelm small-town civic spirit. Such changes, they hypothesized, would lead to a weakening of local community standards and, ultimately, to widespread alienation.

Studies underwritten by the U.S. Department of Agriculture in the early 1940s reinforced the notion. The agency focused on six representative communities, which all revealed a pattern of decline, depopulation and instability reflecting the effect of urban industrial expansion and the Great Depression. The economic turmoil continued in the subsequent decades for various reasons. Harmony (Putnam County), Ga., suffered from depopulation and racial divisions. Landaff, N.H., saw a nearly complete disappearance of its dairy farms over the next 40 years. Irwin, Iowa, suffered from a dramatic decrease in the number of farms, the withering of local businesses, and an aging population.

Even those communities thought to be the most stable—El Cerrito, N.M., and the Old Order Amish of Lancaster County, Pa.—were threatened, with the former losing almost its entire population. Sublette, Kan., ravaged by the dust storms of the 1930s, was considered the least stable in the 1940s, but it survived and grew because of an increasingly industrialized system of agriculture as well as an expansion of natural gas production.

The USDA sponsored a reexamination of these six communities in the 1990s. Surprisingly, the agency found that social organization and civic spirit in all six had remained intact in the face of traumatic economic developments. In Harmony, for example, a concerned citizens group formed in order to address tax inequality. In Irwin, people banded together to help neighbors devastated by fire. In Landaff, the community organized to support a local school. In El Cerrito, residents cooperated to control flood damage. Among the Amish, the traditional barn raising continued. And in Sublette, participation in community organizations increased.

Though broadly representative, the six communities do not constitute a scientific sample and may not mirror the experience of some rural areas, such as the southeastern poverty belt or the northern Plains states, where climate and other conditions may make socioeconomic progress problematic.

These six communities and others fared well in part by finding alternatives to farming. Whereas rural America still provides most of the nation's food and fiber, as the map illustrates, it is now home to other activities. Today farming constitutes only 6 percent of rural America's jobs; 16 percent comes from manufacturing and 53 percent from services, such as retail trade, recreation facilities, education, and health care. Rather than destroying old values, better communications and transport have enabled people to develop a broader range of relationships, and there is no evidence of widespread alienation.

Rodger Doyle can be reached at rdoyle2@adelphia.net

LEAVING THE FARM

Percent of U.S. population in rural areas

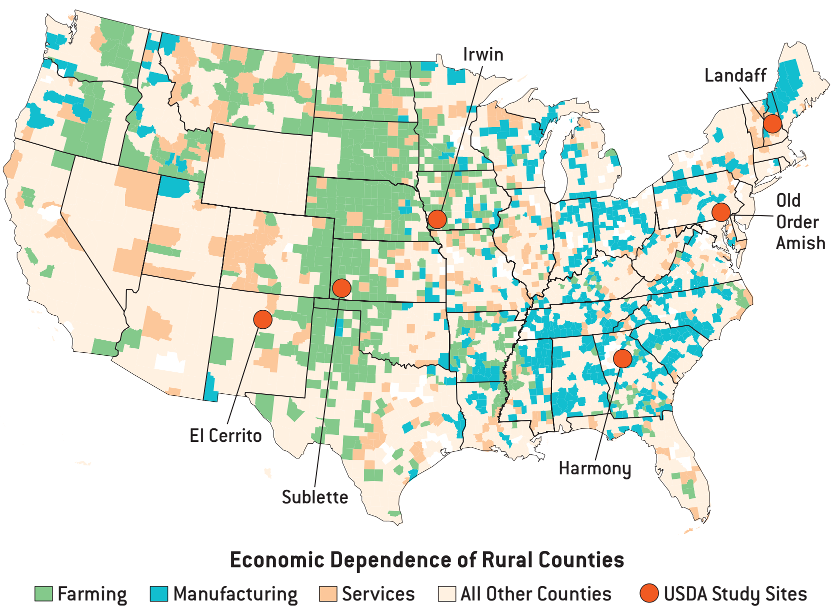
Year	Percent
1800	93.9
1850	84.6
1900	60.4
1950	36.0
2000*	17.4

**Based on new USDA definitions of rural areas in 2003*

FURTHER READING

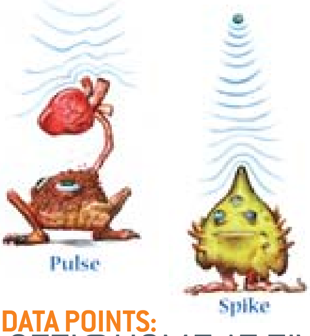
Persistence and Change in Rural Communities: A 50-Year Follow-up to Six Classic Studies. Edited by Richard S. Krannich and A. E. Luloff. CABI Publishing, 2002.

Challenges for Rural America in the Twenty-First Century. Edited by David L. Brown and Louis E. Swanson. Pennsylvania State University Press, 2003.



SOURCES: Economic Research Service, U.S. Department of Agriculture (map and table). On the map, "all other counties" includes metropolitan counties plus rural counties dependent on activities other than farming, manufacturing and services. The data are based on a typology issued in 1989. A new typology now in progress will most likely show the same overall pattern but with a substantial reduction in the number of counties devoted to farming.

RODGER DOYLE



DATA POINTS: SETI@HOME AT FIVE

In May 1999 David Anderson and Dan Werthimer of the University of California at Berkeley founded SETI@home. During down times, personal computers look for signals of extraterrestrial intelligence from data collected by the Arecibo radio telescope. Candidate signs are radio spikes, pulses, triplets (a series of three spikes) and "gaussians," signals that vary in a particular way. The Planetary Society has honored the most prolific data crunchers—individuals, clubs, schools, companies and government agencies, including one identifying itself as the Ministry of Silly Walks. So far all the signals have turned out to be of earthly origin.

Number of participants: **5 million**

Number of countries: **226**

Percent of visible sky covered at least once: **95.7**

Number of candidate:

Spikes: **6.2 million**

Pulses: **592 million**

Triplets: **562 million**

Gaussians: **426 million**

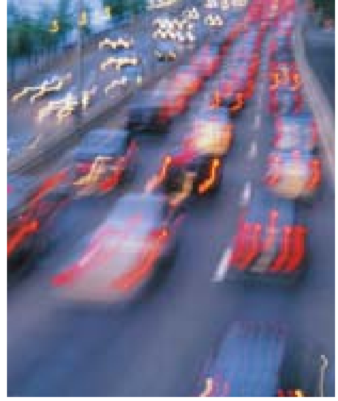
Percent of data verified: **64.8**

SOURCES: SETI@home; The Planetary Society. Top 10 teams are at www.planetary.org/setiteams.html

Data as of June 2, 2004

OPTIMIZATION

I Don't Brake for Bogotá



MOVING dense traffic faster may demand aggressive driving.

Traffic in Colombia's capital city of Bogotá consists of more than a million cars, trucks and buses, but the city's packed highways still keep more cars cruising than other major cities do, say physicists Jose Daniel Muñoz and Luis Eduardo Olmos of the National University of Colombia. They videotaped a car as it drove and then constructed rules for acceleration and braking in a cellular automaton traffic model, in which cars are points on a grid responding to neighboring points. According to the model, the key is aggressive driving—getting nearly bumper-to-bumper before slowing down. The toll for that higher flow: car accidents cause at least one in six violent deaths in Colombia, the researchers say in a paper submitted to the *International Journal of Modern Physics C.* But that rate is actually lower than some traffic-laden U.S. cities, such as Atlanta. *—JR Minkel*

ECOLOGY

Salmon versus Salmon

Genetically engineered salmon can grow more than seven times larger than native counterparts, raising concerns that the supersizing fish would outcompete their wild cousins if they escaped from their farms. In lab experiments, researchers at the government organization Fisheries and Oceans Canada found that the threat occurs when food is scarce. Engineered fish became aggressive over food—in fact, they grew larger than engineered fish given a sufficient diet. Meanwhile the nonengineered salmon in mixed tanks suffered in size compared with their counterparts in tanks without the super salmon. Under low-ration conditions, wild salmon alone in tanks survived and even put on weight. But tanks containing either mixed or engineered-only populations ultimately experienced population crashes and total extinctions, apparently because of malnutrition or cannibalism. The scientists, who published their findings online June 7 in the *Proceedings of the National Academy of Sciences USA,* cautioned that their lab study might not reflect what might happen in more complex natural ecosystems. *—Charles Choi*

THIS BIG: Size matters for salmon.

NEUROBIOLOGY

May Cause Wakefulness

Histamine is best known as the allergy hormone behind inflammation, runny noses, watery eyes and airway constriction, but it appears to be involved in wakefulness as well. Cells containing histamine, along with norepinephrine and serotonin, are active in waking and inactive in sleep. To pinpoint what roles the three chemicals play in the loss of both consciousness and muscle tone during sleep, scientists looked at narcoleptic dogs. Narcoleptics can experience cataplexy—their bodies go limp while they remain conscious. Histamine cell activity continued during cataplexy, suggesting the chemical is linked to waking, whereas norepinephrine and serotonin cell activity ceased in cataplexy, showing they are linked to muscle tone. The findings could lead to drugs that induce sleep or increase alertness and help explain why antihistamines trigger drowsiness. The researchers reported their findings in the May 27 *Neuron.* *—Charles Choi*

THOM LANG *Corbis* (*top*); DAN LAMONT *Corbis* (*bottom*); ILLUSTRATION BY MATT COLLINS

ARCHAEOLOGY

Machine Made

Intricate carvings on the best jades from ancient China were evidently etched by compound machines at least three centuries before such devices were thought to be invented in the West. The first historical references to compound machines, which employ several forms of movement, do not occur until first-century A.D. writings credited to Hero of Alexander. (A simple machine, such as a potter's wheel, uses only one form of motion.) Harvard University physics graduate student Peter Lu looked at ornamental jade burial rings from the Spring and Autumn period (771 to 475 B.C.) and found that the uniformity and precision of their grooves—some conforming within 200 microns of ideal Archimedean spirals—strongly argue for origins in compound machines. Lu suggests in the June 11 *Science* that a stylus suspended over a rotating turntable could have traced the spirals. —*Charles Choi*

SCRATCH THAT: Replica of a machine possibly used to cut spirals on jade.

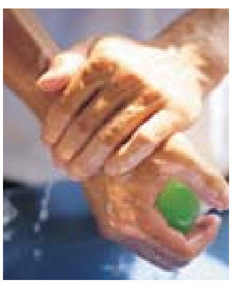
ETCHINGS follow a so-called Archimedean spiral (*white lines*).

HEALTH

Soaping up without Guilt

Antibacterial soaps and toothpaste could be getting a bad rap when it comes to creating superbugs. Peter Gilbert and his colleagues from the University of Manchester and Procter & Gamble isolated 17 bacteria from a kitchen sink and exposed them for up to three months to so-called quaternary ammonium biocides. Some pure strains of each bacterium subsequently developed greater or lesser susceptibility to biocides and antibiotics, but a mixture showed no signs of resistance changes.

"It takes time for resistance to emerge, and we shouldn't be complacent," counters Stuart Levy of Tufts University, who in 1998 found that *E. coli* evolved resistance to a different but common biocide, triclosan. He points out that no study has yet shown that biocides benefit healthy households more than plain soap and water do, and harmless bacteria in the home are exhibiting antibiotic resistance. Levy and the Manchester group agree it would be better for antibacterials to leave no residue for other bacteria to encounter. See the May *Microbiology Today* and the June *Applied and Environmental Microbiology* for the Manchester research. —*JR Minkel*



ANTIBACTERIAL SOAPS may not breed superbugs.

EVOLUTION

Sexual Healing

Sex arose as a means to mix DNA and thereby boost genetic diversity, according to standard evolutionary theory. But it may also exist to help repair DNA damaged by environmental stress, such as heat, for fitter offspring. Work supporting this idea exists for single-celled life-forms, so evolutionary biologist Richard Michod of the University of Arizona at Tucson and his associates experimented on a multicellular species, the green alga *Volvox carteri,* which can reproduce both sexually and asexually. *Volvox* colonies heated for 10 minutes to 42.5 degrees Celsius had twice the number of DNA-damaging oxidants as unheated ones. Researchers found that these high oxidant levels triggered the microbe's genetic pathway for sexual reproduction, leading the algae to release mating pheromones. The report appears in the June 9 *Proceedings of the Royal Society of London B.* —*Charles Choi*

BRIEF POINTS

- **In men with levels of the prostate-specific antigen (PSA) thought to be normal, 15.2 percent actually had prostate cancer, making it unclear what the threshold PSA level should be.**

  New England Journal of Medicine, May 27, 2004

- **A virtual observatory, pulling together data from many telescopes, has found 31 supermassive black holes. Besides validating virtual astronomy, the finding suggests that such objects are two to five times more common than previously thought.**

  Astronomy and Astrophysics (in press); *Institute of Physics/ Physics Web,* June 2, 2004

- **In a hospital study, 47.6 percent of neckties worn by clinicians harbored bacteria that could cause disease.**

  Meeting of the American Society for Microbiology, May 2004

- **Men behaving "manly," showing little emotion and not sharing their feelings, do not develop significantly more psychological distress and relationship problems than their sensitive counterparts do.**

  Psychology of Men and Masculinity (in press)

ROSE LINCOLN *Harvard University News Office* (*top*); PRIVATE COLLECTION (*middle*); CORBIS (*bottom*)

Penny-wise Smart Labels

If smart tags cost only one cent apiece, they would be everywhere By STEVEN ASHLEY

Suppose you could go to the supermarket, fill the shopping cart with goods, and then just walk out the door without having to stand on a checkout line. Like an automated highway-toll collection system, an electronic reader at the store's exit would interrogate radio-based smart labels affixed to each item in the basket and ring up the purchases on a networked computer. Sometime later you would receive the grocery bill, perhaps by e-mail.

Smart labels, or what engineers call radio-frequency identification (RFID) tags, today cost from 30 to 50 cents each, an expense that makes attaching them to most consumer products uneconomical. If that price could be reduced to one cent a tag, however, retailers and many other businesses could implement large-scale, even globe-spanning RFID systems that eventually could save everyone—consumers and producers alike—considerable time and money. Penny smart tags would permit manufacturers to track perhaps billions of goods efficiently throughout the entire supply chain, from warehouse to store to purchaser, and maybe even all the way to the dump.

SMART PORTAL equipped with an RFID tag reader identifies and inventories an incoming shipment of foodstuffs stored in crates fitted with computerized smart labels. The high cost of RFID tags currently limits their use to labeling multicomponent loads of goods rather than individual items.

Cheaper smart-label technology has become a prime target market for silicon chipmakers. Munich-based Infineon Technologies AG, the world's sixth largest semiconductor manufacturer, revealed recently a potentially much lower-cost approach to engineering smart labels, one that employs integrated circuits that are directly powered by alternating current (AC) instead of the standard direct current (DC).

RFID tags have two main components: a silicon chip and a metal coil antenna. When the tag comes within about a meter of an electronic device called a reader, its antenna picks up the reader's weak radio signal. Magnetic induction from the oscillating field drives the silicon chip, which contains logic circuitry and nonvolatile memory. The memory can store information—item type, manufacturing date and price—related to the product to which it is attached, even if it has not been powered up for several years. The chip modulates the incoming signal to retrieve and send its encrypted data to the reader through a simple loop antenna, which operates at a transmission frequency of 13.56 megahertz.

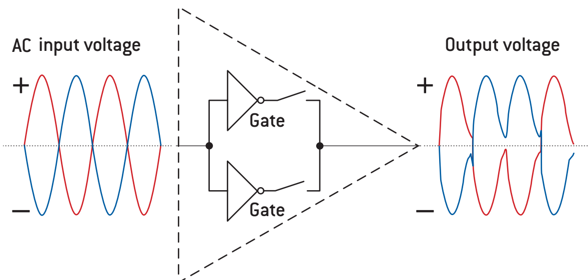
Manufacturers of the current generation of RFID tags spend one third of the fabrication cost to make the chip, a third for the antenna and another third on the packaging, which attaches the chip to the antenna. "So to get to one-cent RFIDs, we need to crank down the costs of all the components," says Werner Weber, a physicist who serves as senior director of corporate research at Infineon.

Eight Infineon engineers began investigating how to

COURTESY OF TIBBETT & BRITTEN

make inexpensive RFIDs from silicon about a year ago. They soon focused on a fundamental trick that might open a pathway to their goal: using AC-driven logic circuitry, a technique that precludes the need for conversion of external AC to internal DC power. "There's been no previous work in this area because there really aren't any other potential applications for the technology that anybody can think of," Weber notes.

A standard silicon-based RFID chip is typically driven by a one- to two-volt DC power supply, the physicist explains. These devices generally incorporate various space-hogging components, ranging from buffers



AC LOGIC CIRCUIT allows an Infineon RFID chip to be powered by alternating current rather than the standard direct current, a feature that reduces its complexity and cost. Pairs of special semiconductor gates (*shown in schematic form at center*) handle either the positive or the negative segments of dual sinusoidal AC voltage inputs.

NINA FINKEL

that store electrical energy to power-limiting diodes to clock generators that emit signals to synchronize the functioning of the electrical circuitry. "By directly applying the AC voltage produced by the reader, we eliminate many of the circuit blocks that convert AC to DC," he states. Thus, manufacturing costs for these RFIDs should fall significantly.

The AC-based concept was achieved by fabricating each chip with reciprocal logic circuits that handle separately the positive or the negative segments of the sinusoidal AC input signal. One circuit processes the rising (positive) part of the sinusoidal wave; the other takes care of the descending (negative) part. When one circuit switches on, the other is deactivated.

A single circuit operates poorly if it tries to handle both halves of the varying signal, so the chip's basic logic gates, which perform NOR and NAND digital logic operations, were redesigned to optimize them for only the positive or the negative part of the AC input. A semiconductor switch turns the tandem circuits on and off as needed.

The unusual AC RFID chip configuration takes up about half the space of conventional DC designs. Using transistors fabricated with tiny circuits (a 0.13-micron complementary metal oxide semiconductor (CMOS) that handles 32-bit processing), the resulting lab-bench test system occupies only 0.02 square millimeter—about the size of a sand grain.

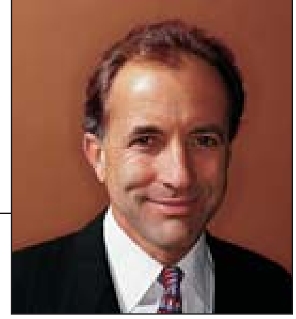
Costs for manufacturing the antennas could be cut significantly by using a new fabrication method based on a powder-sintering process. The technique involves taking inexpensive metal-powder grains and enhancing their size until they fuse together to form the finished antenna.

To lower packaging expense, Infineon researchers developed a new procedure that relies on larger-than-normal electrical contacts on the sides of the silicon chip. This feature facilitates the connection of electrical leads to the antenna using low-precision, very high throughput industrial part-placing equipment.

When the prototype was tested by applying an external AC field to it, its performance met the development team's expectations. "We believe we have proved in principle the concept of AC-powered smart labels," Weber concludes. "This means that a one-cent RFID tag appears feasible." He expects to see a fully operating device in three years, with market introduction occurring in six to 10 years. Before then, in perhaps two to three years, a 10- to 20-cent silicon tag (based on massive increases in production volumes and new manufacturing technologies) should become available from Infineon.

As the cost of RFID tags drops, the number of applications will grow exponentially. Ultimately the goal is to replace the bar codes used for inventory control and intelligent logistics systems in warehouses and food stores with an electronic solution. According to figures provided by the market research organization Allied Business Intelligence, by 2007 these applications will account for worldwide sales worth around $1 billion a year.

If smart labels do get attached to most consumer products during the next few years, one class of frequent store-goers—shoplifters—may find themselves increasingly out of luck. If an RFID tag reader cannot find a valid electronic account to bill for the goods in the basket, it may just bar the malefactor's exit by shutting tight the store's automated doors. SA



BRAD HINES

Miracle on Probability Street

The Law of Large Numbers guarantees that one-in-a-million miracles happen 295 times a day in America   By MICHAEL SHERMER

Because I am often introduced as a "professional skeptic," people feel compelled to challenge me with stories about highly improbable events. The implication is that if I cannot offer a satisfactory natural explanation for that particular event, the general principle of supernaturalism is preserved. A common story is the one about having a dream or thought about the death of a friend or relative and then receiving a phone call five minutes later about the unexpected death of that very person.

I cannot always explain such specific incidents, but a principle of probability called the Law of Large Numbers shows that an event with a low probability of occurrence in a small number of trials has a high probability of occurrence in a large number of trials. Events with million-to-one odds happen 295 times a day in America.

In the course of any normal person's life, miracles happen roughly once a month.

In their delightful book *Debunked!* (Johns Hopkins University Press, 2004), CERN physicist Georges Charpak and University of Nice physicist Henri Broch show how the application of probability theory to such events is enlightening. In the case of death premonitions, suppose that you know of 10 people a year who die and that you think about each of those people once a year. One year contains 105,120 five-minute intervals during which you might think about each of the 10 people, a probability of one out of 10,512—certainly an improbable event. Yet there are 295 million Americans. Assume, for the sake of our calculation, that they think like you. That makes $\frac{1}{10{,}512} \times 295{,}000{,}000 = 28{,}063$ people a year, or 77 people a day for whom this improbable premonition becomes probable. With the well-known cognitive phenomenon of confirmation bias firmly in force (where we notice the hits and ignore the misses in support of our favorite beliefs), if just a couple of these people recount their miraculous tales in a public forum (next on *Oprah!*), the paranormal seems vindicated. In fact, they are merely demonstrating the laws of probability writ large.

Another form of this principle was suggested by physicist Freeman Dyson of the Institute for Advanced Study in Princeton, N.J. In a review of *Debunked!* (*New York Review of Books*, March 25), he invoked "Littlewood's Law of Miracles" (John Littlewood was a University of Cambridge mathematician): "In the course of any normal person's life, miracles happen at a rate of roughly one per month." Dyson explains that "during the time that we are awake and actively engaged in living our lives, roughly for eight hours each day, we see and hear things happening at a rate of about one per second. So the total number of events that happen to us is about thirty thousand per day, or about a million per month. With few exceptions, these events are not miracles because they are insignificant. The chance of a miracle is about one per million events. Therefore we should expect about one miracle to happen, on the average, every month."

Despite this cogent explanation, Dyson concludes with a "tenable" hypothesis that "paranormal phenomena may really exist," because, he says, "I am not a reductionist." Further, Dyson attests, "that paranormal phenomena are real but lie outside the limits of science is supported by a great mass of evidence." That evidence is entirely anecdotal, he admits. But because his grandmother was a faith healer and his cousin was a former editor of the *Journal for Psychical Research* and because anecdotes gathered by the Society for Psychical Research and other organizations suggest that under certain conditions (for example, stress) some people sometimes exhibit paranormal powers (unless experimental controls are employed, at which point the powers disappear), Dyson finds it "plausible that a world of mental phenomena should exist, too fluid and evanescent to be grasped with the cumbersome tools of science."

Freeman Dyson is one of the great minds of our time, and I admire him immensely. But even genius of this magnitude cannot override the cognitive biases that favor anecdotal thinking. The only way to find out if anecdotes represent real phenomena is controlled tests. Either people can read other people's minds (or ESP cards), or they can't. Science has unequivocally demonstrated that they can't—QED. And being a holist instead of a reductionist, being related to psychics, or reading about weird things that befall people does not change this fact. SA

Michael Shermer is publisher of Skeptic *(www.skeptic.com) and author of* The Science of Good and Evil.

From Finish to Start

Was the Grand Challenge robot race in March the fiasco it appeared to be? Hardly, argues William "Red" Whittaker. The annual event is pushing mobile robotics to get real By W. WAYT GIBBS

Late this past February, with less than three weeks remaining before the first ever long-distance race for robotic vehicles, William "Red" Whittaker left Carnegie Mellon University to spend a weekend in the Mojave east of Carson City, Nev. Desert testing of the autonomous humvee that Whittaker's "Red Team" was building had begun there 18 days before.

FOREST McMULLIN

RED WHITTAKER: MAKING ROBOTS WORK

- His first large-scale robots helped to decontaminate the Three Mile Island nuclear power plant; a more recent machine prowled Antarctic ice sheets and discovered exposed meteorites.
- Operates a 1,000-acre farm, growing barley, hay and oats (without robotic help); raises 350 steer from calves every year.
- Former mountain climber; once was forced by an electrical storm to spend the night in the open on the snowy cap of the Matterhorn.

"Yesterday the vehicle drove itself at 32 miles per hour for eight miles along the old Pony Express trail," Whittaker said proudly as he showed off the humvee, named Sandstorm, to a sponsor he had brought with him from Pittsburgh. By the normal standards of mobile robotics, that would be a culminating demonstration for a research project. But to Whittaker, an eight-mile test was just a baby step. The Grand Challenge race would be 142 miles of perilous mountain switchbacks and rough, sandy trails.

After the sponsor departed, the imposing ex-Marine leaned into the window of the SUV in which his team members Chris Urmson, Kevin Peterson and Yu Kato were hunched over laptops, debugging some of the 500,000-odd lines of software in the robot. "Let's be real clear," Whittaker said, stone-faced. "It's important to clock 1,000 miles on Sandstorm, and we haven't done much yet." Send it on a 250-mile journey within the week; only that will catch those subtle but fatal flaws that remain. "It is a sea change in what's to be done," he said.

A sea change in robotics: to Whittaker, who directs the Field Robotics Center at Carnegie Mellon, that is what the Grand Challenge competition is really about. Although the Defense Advanced Research Projects Agency (DARPA) may have sponsored the race to encourage the development of self-driving battlefield vehicles, neither the Red Team nor many of the other 15 that made it to the starting line in mid-March cared much about that aim. Some may have been attracted by the prize money or the glory. Yet the $1-million purse that DARPA offered to the first robot to finish the course in less than 10 hours would barely have covered the loans that Whittaker had taken out to keep his team afloat. As for glory, Whittaker thrives on it. But having pioneered robotic dump trucks, crop harvesters and mine mappers, among many others, he is already famous within the cloistered world of robotics.

The 56-year-old Whittaker sees the Grand Challenge as worthwhile mainly because it is helping to push robots out of the lab and into the real world. That has been a theme in his career. "I was tempered early by a culture around robotics that bordered on the irresponsible," he says. "Our field was strongly influenced by science fiction. There was a tremendous amount of speculation and extrapolation that lacked the integrity of implementation." Most robotics experiments were limited to individual sensors, computer-simulated robots, or machines that only worked in tightly controlled situations. Whittaker focused on bigger pictures.

"Other people build a solution first and then look around to see what they can do with it," observes Michael Montemerlo, a roboticist at Stanford University. "Red chooses a problem and then tries to solve it: Like, how do we send a robot into a nuclear reactor? Or how do you get a robot down to the bottom of a volcano?" (Whittaker has led teams that accomplished both those feats.) "He's not afraid," Montemerlo adds, "to try something and fail"—as the Grand Challenge demonstrates.

Of the 15 vehicles wheeled into the starting chutes at sunrise on March 13, just nine were able to take off, and none got anywhere near the finish line. A modified SUV built by students at the California Institute of Technology crashed through a fence less than two miles down the road and got hung up on the other side. A 14-ton, six-wheeled Oshkosh truck automated by a group based at Ohio State University got flummoxed by sagebrush, reversed, and never moved forward again. Second place went to a dune buggy retrofitted by engineers at Elbit Systems, an Israeli military contractor. Like the Red Team, they had devoted a month to desert testing. But their robot crashed into an embankment 6.8 miles into the race.

Sandstorm put in the best attempt. In the course of its 7.4-mile run, the driverless humvee took out two fence posts, plowed over a concrete-embedded buried-cable warning sign, was knocked off the road by a rock, and reversed to get back on track. Finally, the robot cut a corner in a hairpin turn on the side of a mountain, sending its left wheels over the edge and its chassis into a boulder.

That performance impressed Clint Kelly, head of advanced technology programs at San Diego–based Science Applications International. In the last series of tests of that the U.S. Army conducted, he noted, the best driverless vehicles required rescue by a human every 2.6 miles on average, and the median speed was under four miles per hour. By comparison, Sandstorm went almost three times as far and four times as fast. "And it probably could have gone much further on easier terrain," Kelly says.

Indeed, in one pre-race test Sandstorm drove 57 miles at speeds up to 35 mph without incident. But three days later, as Urmson and the others set out to get the 250-mile test run that Whittaker had demanded, they made a tiny change to Sandstorm's steering software and pushed the speed a bit too hard. The humvee flipped onto its head. In the rush to make repairs, critical tests—those that might have exposed the robot's dangerous tendency to cut corners—never got done.

"The Grand Challenge is still a challenge; it is still out there," Whittaker reminded his team after they all returned to Pittsburgh. He was already lining up sponsors and team members for the next race. DARPA has set the date for October 8, 2005, and has raised the prize to $2 million.

"The competition is going to be much stronger this next time," predicts Montemerlo, who has formed a new team at Stanford. New groups have also sprung up at the Massachusetts Institute of Technology, the Florida Institute of Technology and the Rochester Institute of Technology. "It may now be a question of who finishes fastest rather than who just finishes," Montemerlo suggests.

HEAD OVER WHEELS, the Sandstorm robot crashed in a test four days before the competition. A change of a single digit in its steering and speed control software caused the robot to go too fast on a turn.

NICK MILLER *The Red Team*

Whittaker agrees and sees two keys to winning both the immediate race and the larger struggle to shove mobile robotics into industry and everyday life. The first necessity is to persuade car, computer and sensor makers that they can profit by working together. Doing that means piquing the interest of the public and of politicians, which DARPA has now done. For the 2005 race, AM General, the manufacturer of military humvees, has donated two Hummer H1s to the Red Team. AMG engineers will be helping the Whittaker group tap into the vehicles' built-in drive-by-wire systems.

The second key, he says, is to teach a generation of young engineers how to invent reliable, robust systems and not just parts for demonstrations. "Youthful exuberance and passion matter," Whittaker says. "But the real question is whether that kind of chaotic community can grow up and advance to the next level." That means inculcating a culture where most of the work goes into testing and refining rather than inventing and designing. "It is the most wonderful thing that the race didn't go cheap," he declares. "You're observing a new community hoisting itself up by its bootstraps. And that is actually the biggest thing to come out of the Grand Challenge." SA

Back to the Future of Cereals

Genomic studies of the world's major grain crops, together with a technology called marker-assisted breeding, could yield a new green revolution

BY STEPHEN A. GOFF
AND JOHN M. SALMERON

RICE SEEDLINGS can be genetically tested for desirable traits.

MODERN CORN AND ITS ANCESTOR TEOSINTE look so dissimilar (*drawings*) that their relationship was questioned until genetic investigations confirmed it. By selectively propagating plants with desirable traits, ancient cultivators in what is now Mexico unwittingly favored certain versions of genes that control branching pattern, kernel structure and other attributes. By 4,400 years ago the teosinte cob's hard fruit case (*left photograph*) was gone and plump, modern-looking corn cobs (*right photograph*) carried the versions of the genes that control protein storage and starch quality in all domesticated corn today.

For thousands of years, farmers have surveyed their fields and eyed the sky, hoping for good weather and a bumper crop. And when they found particular plants that fared well even in bad weather, were especially prolific, or resisted disease that destroyed neighboring crops, they naturally tried to capture those desirable traits by crossbreeding them into other plants. But it has always been a game of hit or miss. Unable to look inside the plants and know exactly what was producing their favorable characteristics, one could only mix and match plants and hope for the best.

Despite the method's inherent randomness, it has worked remarkably well. When our hunter-gatherer ancestors started settling down some 10,000 years ago, their development of agriculture allowed human society to undergo a population explosion. It is still expanding, demanding continual increases in agricultural productivity.

Yet 99 percent of today's agricultural production depends on only 24 different domesticated plant species. Of those, rice, wheat and corn account for most of the world's caloric intake. Each of these three extremely important cereals is already produced in amounts exceeding half a billion tons every year. To keep pace with a global population projected to reach nine billion by 2050, while maintaining our present average daily consumption of between 0.9 and 3.3 pounds of these grains per person, cereal crops will have to yield 1.5 percent more food every year and on a diminishing supply of cultivated land.

Plant scientists believe that crop yields have not yet reached their theoretical maximum, but finding ways to achieve that potential increase and to push the yield frontier still further is an ongoing international effort. Encouragingly, a new set of tools is revealing that some of the answers may be found by exploring the origins of the three major cereal crops.

Creating Modern Crops

MOLECULAR AND GENETIC studies are showing that wheat, rice and corn, as well as barley, millet, sorghum and other grasses, are far more interrelated than was once thought, so fresh insights into any one of these crop species can help improve the others. Further, many of these improvements may come from tapping the genetic wealth of our crops' wild ancestors by breeding useful traits back into the modern varieties.

Although the cereal crops are descendants of a common ancestral grass, they diverged from one another some 50 million to 70 million years ago, coming to inhabit geographically distinct regions of the world. Beginning around 10,000 years ago, farmers in the Mediterranean's Fertile Crescent are believed to have first domesticated wheat, and perhaps 1,000 years later, in what is now Mexico, farmers began cultivating an ancestor of modern-day corn. The ancient Chinese domesticated rice more than 8,000 years ago.

As our ancestors domesticated these plants, they were creating the crops we know now through a process very much like modern plant breeding. From the wild varieties, they selectively propagated and crossbred individual plants possessing desirable traits, such as bigger grains or larger numbers of grains. Plants that did not disperse their seeds were appealing, because harvesting their grain was easier, although this characteristic made a plant's propagation dependent on humans. Early cultivators also selected plants for their nutritional qualities, such as seeds with thin coats that could be eaten easily and maize varieties whose starch consistency best lent itself to making tortillas. In this way, crop plants became increasingly distinct from their progenitors and eventually rarely crossed with their wild versions. Corn became so dissimilar to its ancestor, teosinte, that its origin was commonly disputed until very recently [*see illustration above*].

This human modification of cereal plants through selective propagation and

Overview/*Tapping Crops' Genetic Wealth*

- Comparing the genomes of major cereal crop species shows their close interrelationships and reveals the hand of humans in directing their evolution.
- Identifying the functions of individual plant genes allows scientists to search modern crops and their wild relatives for gene versions that confer desirable traits.
- With the desired gene as a traceable marker, traditional crossbreeding can become faster and more precise.

KAY CHERNUSH (*preceding page*); NINA FINKEL (*drawings*); JOHN DOEBLEY (*photographs*) (*this page*) crossbreeding begun during prehistoric times has never stopped. Over the past century, crops have been selected for larger seed-bearing heads to increase their yields. These higher-yielding seed heads are heavy, so shorter plant heights were also bred into rice and wheat to prevent the plants from being bent to the ground by wind. Breeding for disease resistance, environmental stress tolerance and more efficient utilization of nitrogen fertilizers dramatically increased yields and their consistency, producing the green revolution of the 1960s. Corn's average yield per acre in the U.S., for example, has risen by nearly 400 percent since 1950.

Yet even during that boom period, plant breeders had little more to go on than the earliest crop cultivators. Most were limited to visible plant characteristics, or markers, such as seed size or plant architecture, to guide their selection of desirable lines for further propagation.

Still, studies of the genomes of cereal crops illustrate how prehistoric cultivators, by selecting for visible traits, were unwittingly selecting particular genes. For example, a group led by Svante Pääbo of the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany, analyzed the alleles, or versions, of specific genes in corn cobs recovered from sites in Mexico near the origin of corn domestication. Pääbo and his colleagues determined that by 4,400 years ago, domesticated corn already possessed genetic alleles that control the plant's branching pattern as well as aspects of protein and starch quality found in all modern corn varieties. In corn's wild relative, teosinte, these alleles occur in only 7 to 36 percent of plants, indicating that the selection pressure applied by early farmers to favor those alleles was rapid and thorough.

Indeed, working independently on different cereal crop species, breeders have been unknowingly altering them by selecting mutations in similar sets of genes. Trait mapping—narrowing the probable location of the gene underlying a trait to a particular chromosomal region, or locus—has shown that many of the changes humans have made in modern cereals map to similar loci in the genomes of related crop plants. The reason for this similarity is that the structures of these different crops' genomes are themselves so similar, despite millions of years of independent evolution separating the cereal species.

Harvesting Genomes

A FEW THOUSAND trait-controlling loci have now been mapped in various domesticated cereals, revealing the surprising degree to which the plants' overall genetic maps have been conserved. The high degree of this correspondence, known as synteny, between genomes of all the grasses allows scientists to consider them as a single genetic system, meaning that any discoveries of genes or their function in one cereal crop could help scientists to understand and improve the others.

Rice, whose formal name is *Oryza sativa,* is likely to be the first to yield many of these new insights, because it will be the first crop plant to have its entire genome sequenced. One of us (Goff) has already published a draft sequence of the *japonica* subspecies of rice most commonly grown in Japan and the U.S., and Chinese researchers have produced a draft of the *indica* subspecies widely cultivated in Asia. The International Rice Genome Sequencing Project is expected to complete a detailed sequence of rice's 12 chromosomes by the end of this year.

The rice genome is the easiest of all the cereals' to tackle because it is much smaller than the others, with only 430 million pairs of DNA nucleotides. By comparison, the human genome has three billion of these so-called base pairs, as does corn. Barley's genome contains five billion base pairs and wheat, a whopping 16 billion. A corn genome–sequencing project is under way, and one for wheat is under consideration. And from the existing sequence information about rice, tens of thousands of genes have already been identified. Just knowing that a stretch of the genome is a gene does not tell us what it does, though.

Several strategies allow us to determine a gene's function, but the most straightforward involves searching existing databases of all known genes to look for a match. Often genes are responsible for such basic cellular activities that a nearly identical gene will be found in microbes or other organisms whose genes have already been studied. Of the 30,000 to 50,000 predicted genes in rice, approximately 20,000 have sequence similarity, or homology, to previously discovered genes whose function is known,

DESIRABLE TRAITS

Traits that plant breeders seek to modify fall into broad categories, including growth, plant architecture, stress tolerance and nutrient content. Yield increases—the holy grail of agriculture—can be achieved by expanding the size or number of grains produced by a single plant, by enabling more plants to grow in the space usually needed for one, or by making plants tolerant of conditions where they previously could not thrive.

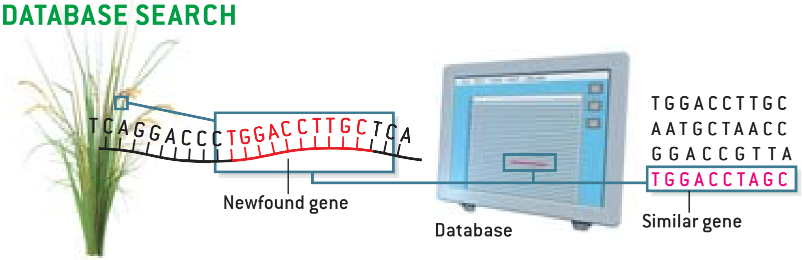
Growth	Architecture	Stress tolerance	Nutrient content/quality
Grain size or number	Height	Drought	Starch
Seed-head size	Branching	Pests	Proteins
Maturation speed	Flowering	Disease	Lipids
		Herbicides	Vitamins
		Intensive fertilization	

DOUG WILSON *Corbis*

MATCHING TRAITS TO GENES

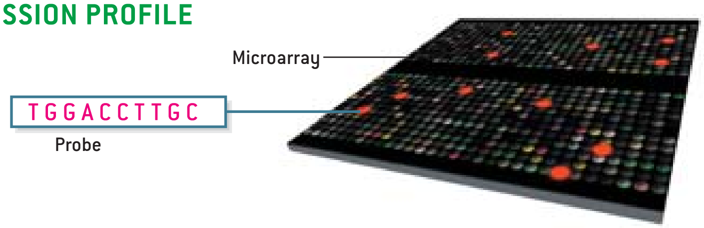
The same tools that allow scientists to trace some human diseases to individual genes make it possible to find the genes responsible for plant attributes. Mapping techniques can narrow the trait-controlling gene's probable location to one region on a chromosome; sequencing of the DNA in that region will then narrow the search to a likely gene. To find out the gene's function, investigators can apply any of the techniques below.

DATABASE SEARCH



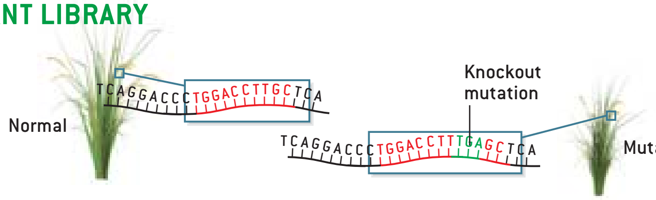
Comparing a newfound gene with known genes in a variety of databases can yield a near match. Of rice's estimated 30,000 to 50,000 genes, 20,000 are similar to genes already studied in other organisms and are assumed to have the same functions.

EXPRESSION PROFILE



Expression profiling gives clues to a gene's function by showing when and where the gene is activated in a plant. A microarray holds thousands of snippets of DNA called probes. Each probe matches a unique signature of gene activity called a messenger RNA (mRNA). When plant cell samples are washed across the microarray, any mRNAs present will stick to their matching probes, causing the probes to emit light. If a gene is expressed, or activated, only during grain development, for example, it is assumed to play a role in that process.

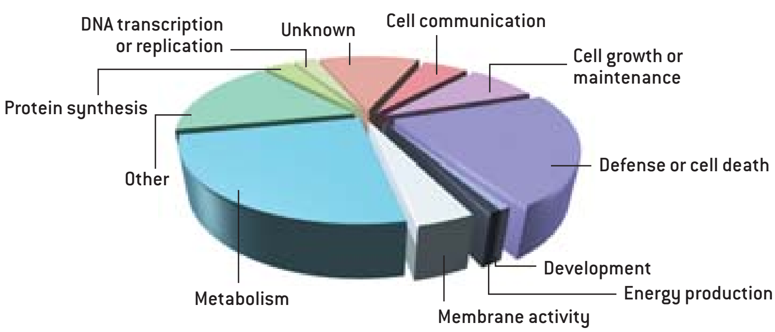
MUTANT LIBRARY



Studying mutants can reveal the function of specific genes by showing what happens when the genes are deactivated. A small piece of DNA inserted into a gene of interest can "knock out," or silence, that gene in the developing plant. Screening the mutant for physical or chemical differences from normal plants can indicate the gene's usual role.

PREDICTED RICE GENE CLASSIFICATIONS

Using the methods described above, investigators have determined or predicted the functions of a large fraction of rice genes.



SLIM FILMS

which allows researchers to predict the role of those genes in rice.

For example, more than 1,000 genes are predicted to be involved in defending rice against pathogens and pests. Likewise, hundreds of genes have been assigned to specific metabolic pathways that lead to the synthesis of vitamins, carbohydrates, lipids, proteins or other nutrients of interest. From experimental data about well-studied plants such as *Arabidopsis* (thale cress), many of the genes that regulate these biosynthetic pathways or affect important stages of crop development, such as flower and seed formation, have also been identified.

A number of research groups have gone further and begun using powerful tools called microarrays to catalogue which genes are expressed, or activated, in a variety of distinct cereal tissues. For example, scientists at our company, Syngenta, examined 21,000 rice genes and identified 269 of them that are preferentially expressed during development of the rice grain, suggesting that these genes play key roles in determining the nutrient composition of the mature grain.

A somewhat different approach to determining a gene's function is to "knock it out" by inserting a mutation into the gene that shuts off its activity and then see what happens to the plant. Sometimes the effect is visible, but the modified plant can also be tested for less obvious changes in any of its normal physiological, developmental, internal regulatory or biochemical functions. Both private and public efforts have completed collections of mutant rice and corn plants in which thousands of specific genes have been knocked out. Such functional genomic studies, combined with sequence comparisons of genes across species, allow scientists to begin developing a basic understanding of how many and which of rice's genes—and by extension those of corn, wheat, sorghum and other cereal crops—contribute to plant development, physiology, metabolism and yield.

Once the function of a specific gene is known, a remaining step in using that knowledge to improve crops is to identify specific alleles of the gene that deliver desirable traits. For example, if a gene is known to control an aspect of starch accumulation in corn grain, a version of the gene can be sought that functions under severe drought conditions. Such desirable alleles may be found in other modern corn varieties, but even more will probably be discovered in wild relatives of crop plants. Genetic homogeneity among modern crops is an adverse consequence of the way our ancestors initially domesticated them. According to one estimate, modern corn's founding population may have comprised as few as 20 plants. By selecting only a few individual plants with desirable traits to propagate and then inbreeding these for thousands of years, early cultivators severely limited genetic diversity in the domesticated species.

Experimenting with both tomato and rice plants, Steven Tanksley and Susan R. McCouch of Cornell University have pioneered searches for beneficial alleles in wild varieties that might improve modern crops. Their work has demonstrated the genetic diversity available in wild relatives of domesticated plants, at the same time showing that the wild varieties' most valuable resources are not always obvious. In one experiment during the mid-1990s, Tanksley crossed a tiny wild green tomato species from Peru with a somewhat pale red modern processing tomato cultivar. Surprisingly, he found that a gene from the green tomato made the red tomato redder. As it turned out, the green tomato lacked certain genes to complete synthesis of the pigment lycopene, which gives tomatoes their red hue, but it did possess a superior allele for a gene that plays a role earlier in the tomato's lycopene synthesis pathway.

The genetic variety in wild relatives of our modern crops is only beginning to be explored. In rice and tomatoes, an estimated 80 percent of each species' total allelic diversity remains untapped. Remarkable studies by Tanksley, McCouch and others have repeatedly demonstrated the ability of wild alleles to produce dramatic changes in physical aspects of domesticated plants, even though some of the changes seem counter to the wild plants' normal attributes, as in the tomato example. So without the technology to use genes or chromosomal loci as molecular markers, scientists will find identifying some of these desirable traits or moving them into modern crops nearly impossible.

AUTHORS JOHN SALMERON (*left*) AND STEPHEN GOFF with experimental corn plants. In the greenhouse, female reproductive parts of the corn plants, called silks, are covered with small white waxed-paper bags to prevent their fertilization by the male reproductive parts, or tassels, at the top of the plant.

KAY CHERNUSH

Marker-Assisted Breeding

ONCE SCIENTISTS HAVE identified specific sets of beneficial alleles from different wild or modern plant varieties, the goal becomes moving just those alleles into a modern crop breeding line, known as an elite cultivar. We could use bacterial DNA or some other delivery vehicle to transfer selected genes, applying the same process (called transformation) used to create so-called genetically modified crops. But scientists are also exploring an approach that avoids the long and expensive regulatory approval process for transgenic plants: breeding guided by genetic markers.

Knowing the exact alleles that confer desirable traits, or even just their chromosomal loci, a breeder could "design" a new plant that combines those traits with the best qualities of an elite cultivar, then build it through crossbreeding with the help of DNA-fingerprinting technology such as that used to determine paternity or solve forensic questions [*see illustration on next page*].

All large-scale plant breeding produces tens of thousands of seedlings. But instead of having to plant each of these progeny and wait until they mature to see if a trait has been inherited, a breeder would simply sample a bit of each seedling's DNA and scan its genes for the chosen allele, which serves as a marker for the desirable trait.

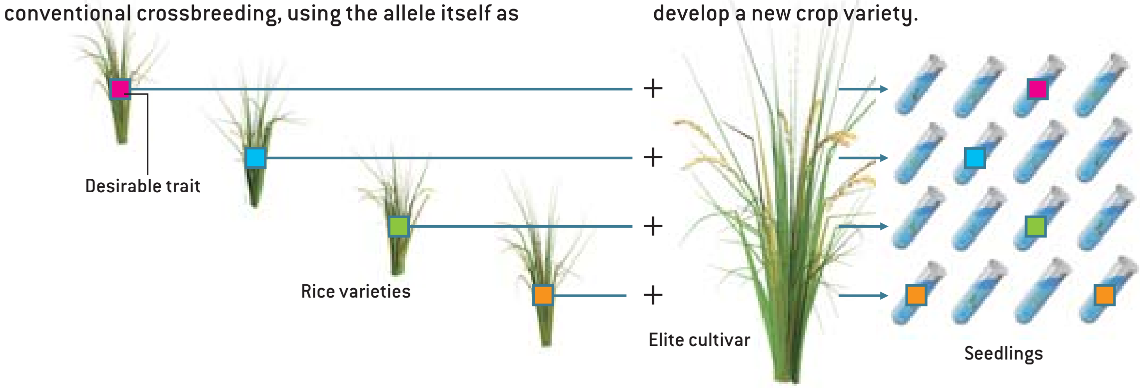
Seedlings possessing the desired allele would be grown until they were ready to crossbreed with the elite cultivar. Those progeny would then be tested for the allele, and so on, until the breeder had a population of plants that resembled the original elite cultivar but for the presence in each of a newly acquired allele. The time savings afforded by using genetic fin-

THE AUTHORS

STEPHEN A. GOFF and *JOHN M. SALMERON* are plant geneticists at Syngenta Biotechnology, Inc., in Research Triangle Park, N.C. Goff led a U.S. team in producing a draft sequence of the rice genome published in 2002. He is currently working on a humanitarian initiative to use genetic information about rice to help crop improvement efforts in developing countries. Salmeron, director of applied trait genetics for SBI, has been applying genetics to crop improvement since 1989, when as a postdoctoral researcher at the University of California, Berkeley, he isolated one of the first plant disease-resistance genes in the tomato.

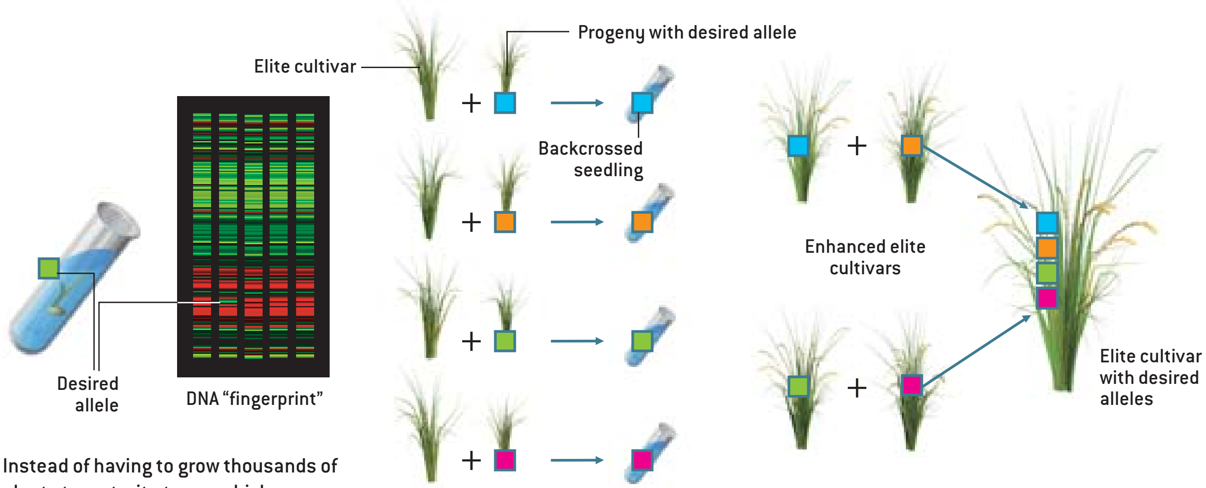
DESIGNING AND BUILDING NEW CROPS

When scientists know which gene controls a specific plant trait, such as seed size, they can search different varieties of the domesticated plant and its wild relatives to find a preferable version, or allele, of the gene. A breeder could then move a desirable allele from one plant into another through conventional crossbreeding, using the allele itself as a traceable marker for the trait. Instead of waiting a full growing season for plants to mature, the breeder could rapidly find out if seedlings have the desired trait by testing them for the allele in each round of breeding. Such marker-assisted breeding would dramatically shorten the time required to develop a new crop variety.



1 Each of four different rice varieties with a desirable trait can be crossed with an elite breeding line, or cultivar, to produce tens of thousands of seedlings.

2 Some, but not all, of the seedlings will inherit the desirable allele.



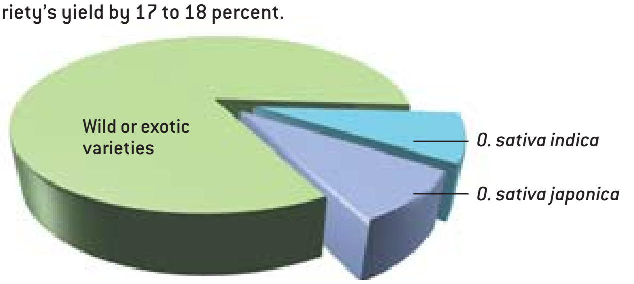
3 Instead of having to grow thousands of plants to maturity to see which ones inherited the trait, breeders can test each seedling's DNA for the desired allele just days after germination with the technology used for so-called DNA fingerprinting.

4 Only progeny with the desired alleles are grown until they are mature enough to breed with the elite cultivar, a step known as backcrossing.

5 Crossing and backcrossing are repeated, with the progeny's genes tested in every round, until all the desired alleles have been moved into the elite crop plant.

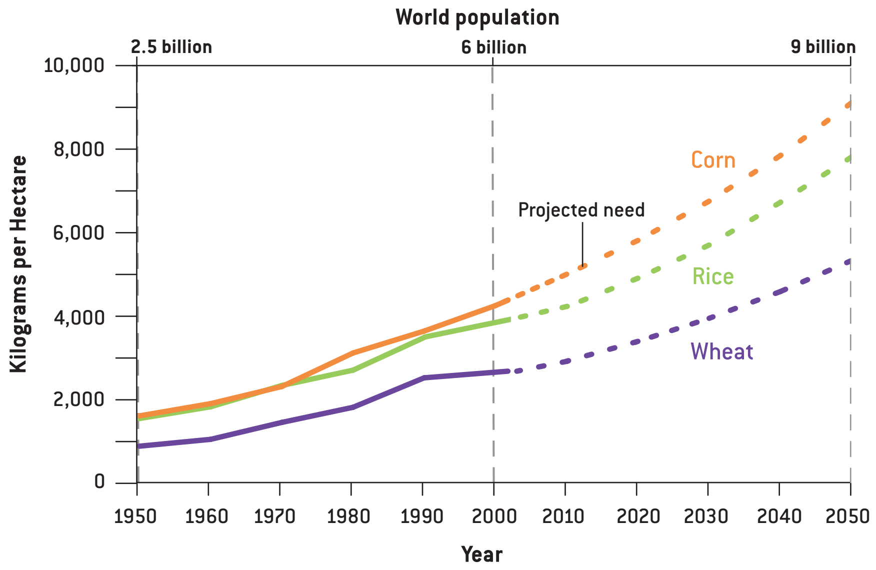
GENETIC DIVERSITY IN RICE

After thousands of years of inbreeding, modern crop varieties are far less genetically diverse than their wild relatives (*pie chart*), making the wild plants a rich reservoir for novel alleles. The untapped wealth in wild plants is not always obvious: in experiments with rice ancestor *Oryza rufipogon* (*left*), alleles from the wild plant were moved into a modern high-yield Chinese rice variety (*right*) using marker-assisted breeding. The low-yield wild plant's genes raised the modern variety's yield by 17 to 18 percent.



O. rufipogon High-yield variety

CEREAL CROP YIELDS



WORLDWIDE AVERAGE YIELDS for corn, rice and wheat nearly tripled between 1950 and 2000, a period that saw global population do the same. To feed a projected world population of nine billion in the year 2050, while maintaining present average consumption of 0.9 to 3.3 pounds per person a day of these cereal crops, yields must keep rising by 1.5 percent a year.

NINA FINKEL; SOURCE: FOOD AND AGRICULTURE ASSOCIATION

gerprinting to test for trait markers at each stage of this process would literally shave years off the time typically required to develop new crop varieties. This acceleration would allow breeders to become more responsive to changing circumstances, such as the emergence of new pests or of resistance among old pests to current countermeasures. Tailoring new crop varieties with combinations of characteristics that are optimized for different environments, farmers' needs or consumer preferences would also become easier.

But the real revolutionary potential in this method lies in its power to open up the genetic bottleneck created thousands of years ago when our major crops were first domesticated. Once scientists accumulate more information about the functions of genes in the grasses, we can more effectively search the huge reservoir of genetic diversity waiting in the wild relatives of modern crop plants. One of McCouch's experiments provides an example of the possibilities: she used molecular markers to identify gene loci in a Malaysian wild ancestor of rice known as *Oryza rufipogon.* McCouch and her colleagues then employed marker-assisted breeding to move a total of 2,000 genes—approximately 5 percent of the rice genome—into plants of a modern Chinese hybrid rice variety.

This experiment was focused on finding alleles to increase the already high-yield hybrid's output still further, and the resulting test plants were examined for several yield-improving traits, such as plant height, length of its flowering head (panicle), and grain weight. Approximately half the wild relative's loci turned out to have yield-improving alleles, although some of these also had negative effects on other aspects of the plants' growth, such as slowing maturation time. But two of the alleles from *O. rufipogon* seemed to have no negative effects and produced yield increases of 17 and 18 percent, respectively, in the modern cultivar. As in Tanksley's tomato experiment, nothing about the wild plant's appearance [*see box on opposite page*] suggested that it could teach modern rice something about yield, yet the results were impressive and encouraging.

Of course, certain beneficial genes cannot be moved into modern crop varieties by means of traditional breeding. For example, genes conferring some types of herbicide tolerance or insect resistance do not exist in plants that will crossbreed with corn.

A gene can be transferred into a recipient plant using current transformation techniques, but they do not allow scientists to specify where in the recipient organism's genome a new gene is inserted. Thus, one could add a new allele but not necessarily succeed in replacing the old, less desirable allele. Yet in the cells of mice and in some microbes, a phenomenon called homologous recombination directs an introduced gene to a chromosomal location whose DNA sequence is most similar to it—permitting a desirable allele of a gene to directly replace the original.

In the future, we may be able to achieve the same one-step substitution of gene alleles in crop plants. Homologous recombination was recently demonstrated in rice, and a related process has been used to replace alleles in corn. Once it becomes routine, the ability to swap pieces of chromosomes this way in the laboratory might allow scientists to exchange alleles between some plants that cannot be crossbred naturally.

Today marker-assisted breeding is already speeding the process in crops of the same species or close relatives. No new cereals have been domesticated in more than 3,000 years, suggesting that we will need to rely on improving our current major crops to meet ever increasing food demands. By providing the ability to peer into plants' genomes and the tools to harvest their hidden treasures, genetic science is opening the way to a new green revolution. SA

MORE TO EXPLORE

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A Draft Sequence of the Rice Genome (*Oryza sativa* L. ssp. *japonica*). Stephen A. Goff et al. in *Science,* Vol. 296, pages 92–100; April 5, 2002.

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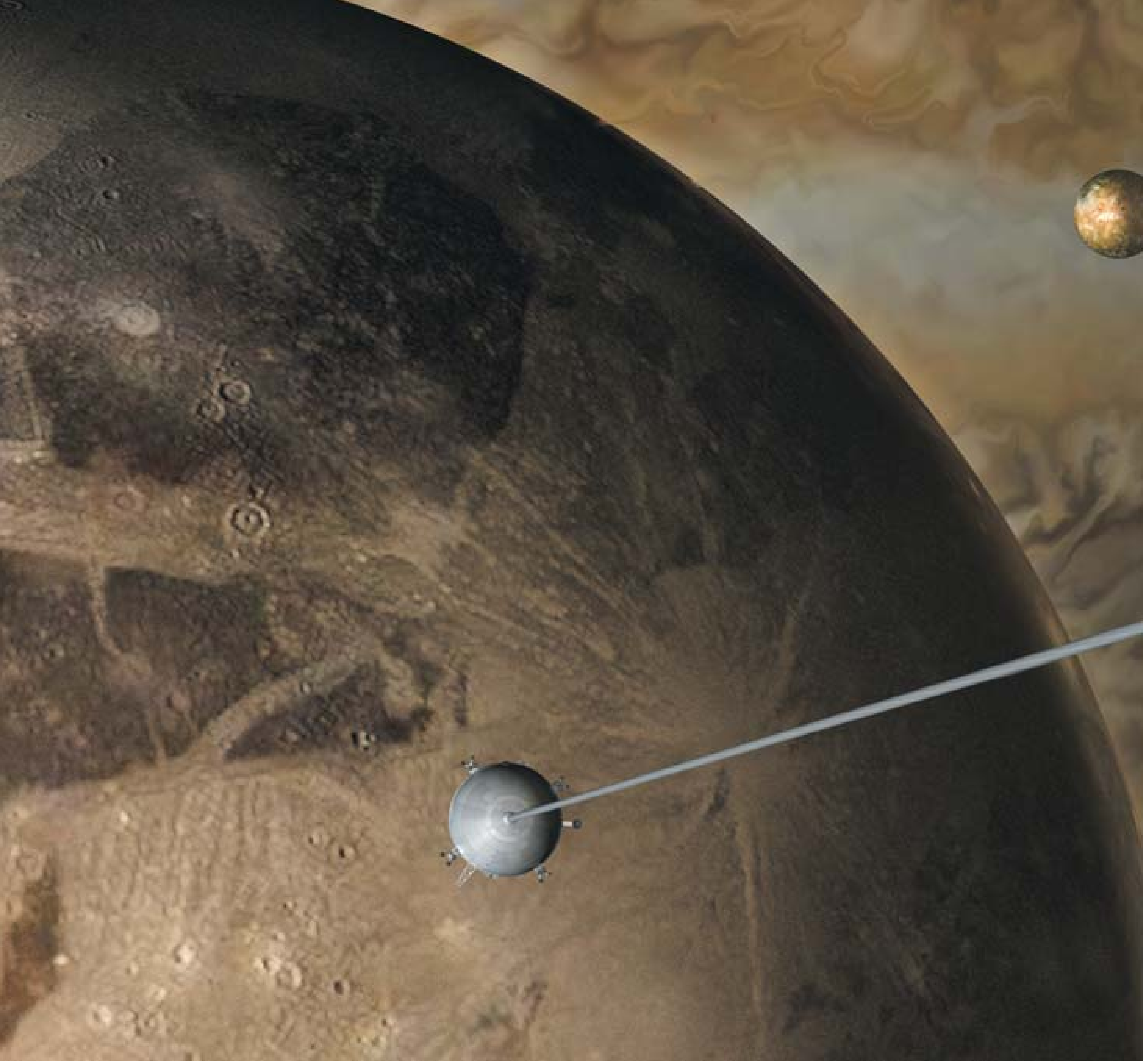
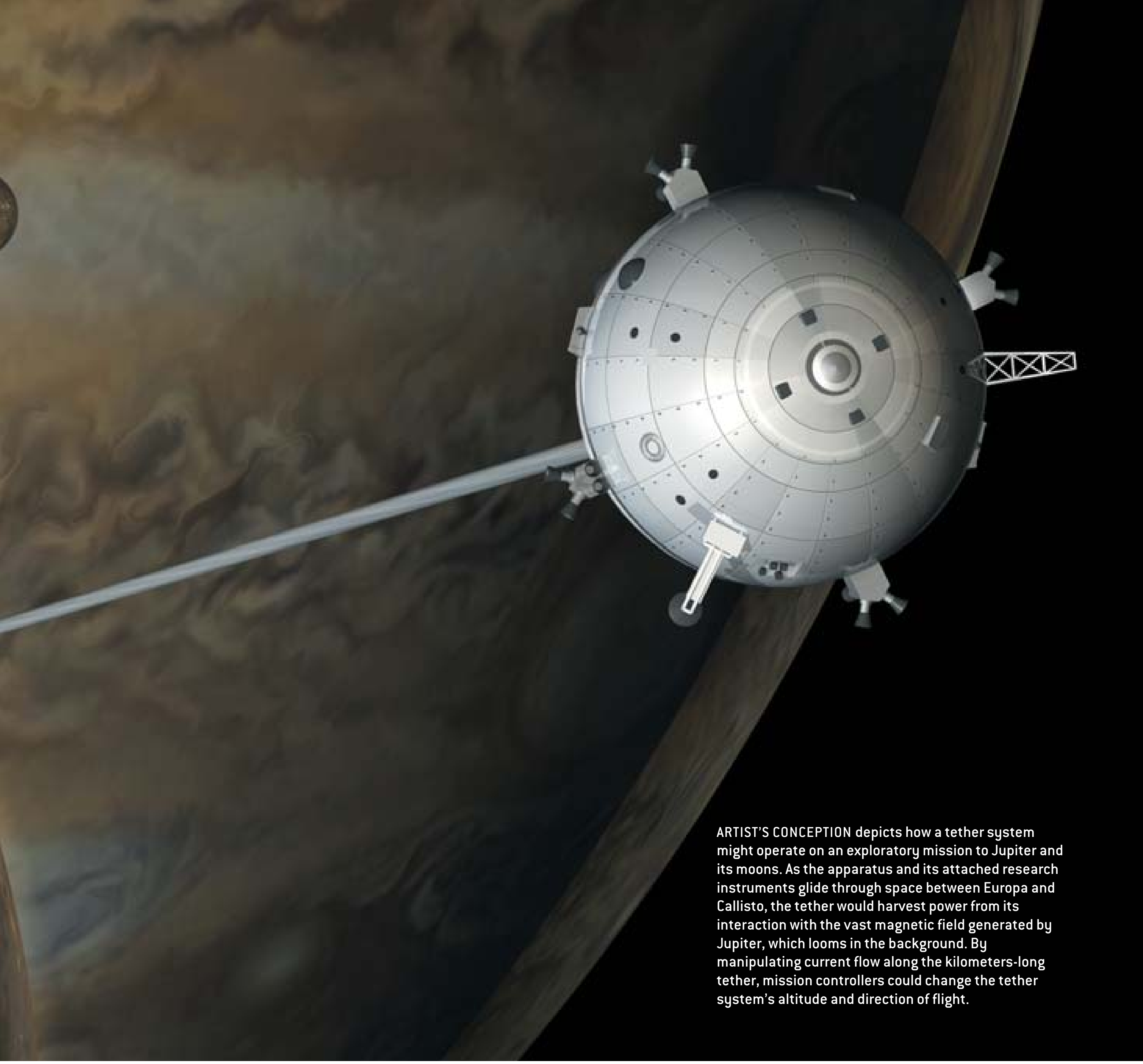


Electrodynamic Tethers in Space

By Enrico Lorenzini and Juan Sanmartín



ARTIST'S CONCEPTION depicts how a tether system might operate on an exploratory mission to Jupiter and its moons. As the apparatus and its attached research instruments glide through space between Europa and Callisto, the tether would harvest power from its interaction with the vast magnetic field generated by Jupiter, which looms in the background. By manipulating current flow along the kilometers-long tether, mission controllers could change the tether system's altitude and direction of flight.

By exploiting fundamental physical laws, tethers may provide low-cost electrical power, drag, thrust, and artificial gravity for spaceflight

There are no filling stations in space.

Every spacecraft on every mission has to carry all the energy sources required to get its job done, typically in the form of chemical propellants, photovoltaic arrays or nuclear reactors.

The sole alternative—delivery service—can be formidably expensive. The International Space Station, for example, will need an estimated 77 metric tons of booster propellant over its anticipated 10-year life span just to keep itself from gradually falling out of orbit. Even assuming a minimal price of $7,000 a pound (dirt cheap by current standards) to get fuel up to the station's 360-kilometer altitude, that is $1.2 billion simply to maintain the orbital status quo. The problems are compounded for exploration of outer planets such as Jupiter, where distance from the sun makes photovoltaic generation less effective and where every gram of fuel has to be transported hundreds of millions of kilometers.

So scientists are taking a new look at an experimentally tested technology—the space tether—that exploits some fundamental laws of physics to provide pointing, artificial gravity, electrical power, and thrust or drag, while reducing or eliminating the need for chemical-energy sources.

Overview/*A New Look at Tethers*

- Electrodynamic tether systems—in which two masses are separated by a long, flexible, electrically conductive cable—can perform many of the same functions as conventional spacecraft but without the use of chemical or nuclear fuel sources.
- In low Earth orbit, tether systems could provide electrical power and positioning capability for satellites and manned spacecraft, as well as help rid the region of dangerous debris.
- On long-term missions, such as exploration of Jupiter and its moons, tethers could drastically reduce the amount of fuel needed to maneuver while also providing a dependable source of electricity.

Tethers are systems in which a flexible cable connects two masses. When the cable is electrically conductive, the ensemble becomes an electrodynamic tether, or EDT. Unlike conventional arrangements, in which chemical or electrical thrusters exchange momentum between the spacecraft and propellant, an EDT exchanges momentum with the rotating planet through the mediation of the magnetic field [*see illustration on opposite page*]. Tethers have long fascinated space enthusiasts. Visionaries such as Konstantin Tsiolkovsky and Arthur C. Clarke imagined using them as space elevators that whisked people from surface to orbit. In the mid-1960s two of the Gemini flights tested 30-meter tethers as a way to create artificial gravity for astronauts, and numerous kinds of tether experiments have taken place since then. The chief challenges are electromechanical: engineers have not yet devised reliable techniques to deal with the high voltages that EDTs experience in space. Nor have they solved all the issues of tether survivability in the hostile space environment or mastered the means to damp the types of vibrations to which EDTs are prone.

Nevertheless, many scientists believe that the technology could revolutionize some types of spaceflight. Its applications cover low Earth orbit as well as planetary missions. EDTs are likely to find uses around Earth for cleaning up orbital debris and generating electricity at higher efficiency than fuel cells as well as keeping satellites in their desired orbits.

A Self-Adjusting System

TETHERS EXPLOIT the sometimes counterintuitive quirks of orbital mechanics. Two countervailing forces act on any object in a stable orbit around a planet: an outward-pulling centrifugal force produced by orbital motion exactly balances a downward gravitational force. The gravity and centrifugal forces offset each other perfectly at the object's center of mass. An observer onboard is in zero *g*, or free fall, and does not perceive any acceleration.

What happens if, instead of one compact satellite, we have two in slightly different orbits, connected by a tether? The teth-

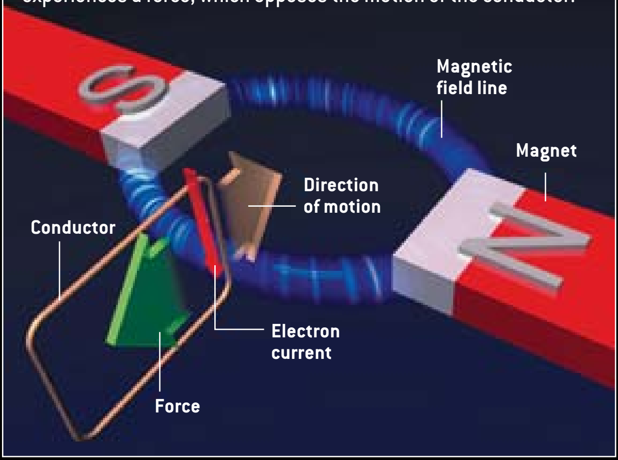
ALFRED T. KAMAJIAN (*preceding pages*)

HOW ELECTRODYNAMIC TETHERS WORK

Electrodynamic tether systems have the potential to accomplish many of the same tasks as conventional spacecraft but without the need for large quantities of onboard fuel. They take advantage of two basic principles of electromagnetism: current is produced when conductors move through magnetic fields, and the field exerts a force on the current.

INDUCED CURRENT

When a conductor moves through a magnetic field, charged particles feel a force that propels them perpendicular to both the field and the direction of motion. An electrodynamic tether system uses this phenomenon to generate electric current. The current, in turn, experiences a force, which opposes the motion of the conductor.



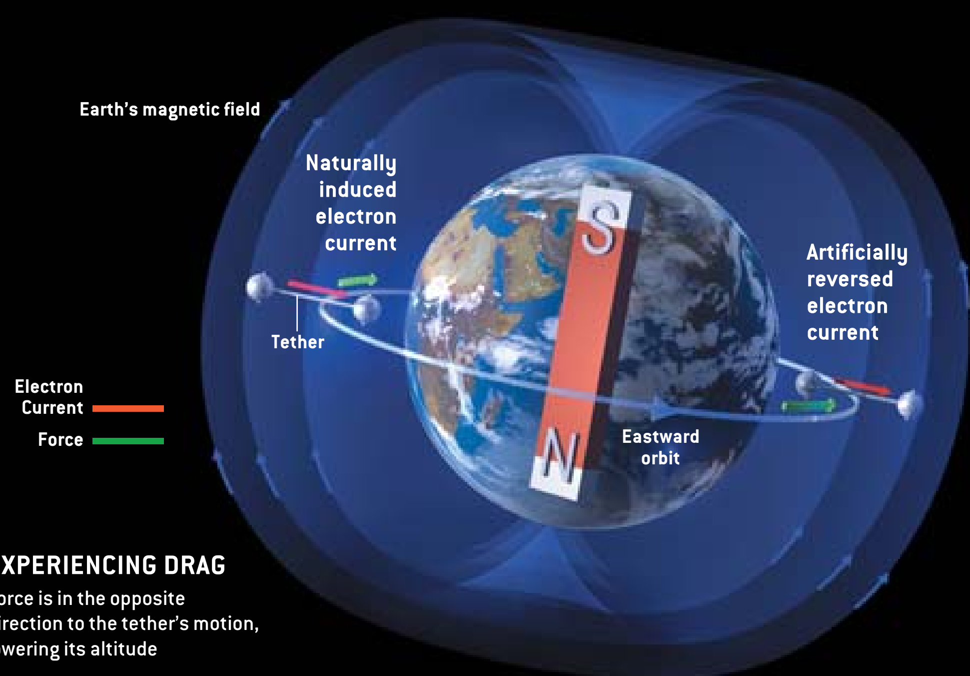
EXTERNALLY DRIVEN CURRENT

A battery added to the circuit can overcome the induced current, reversing the current direction. Consequently, the force changes direction. An electrodynamic tether exploits this effect to produce thrust. (Technical note: These diagrams show the electron current, which is opposite the usual current convention.)

HOW A CURRENT CAN CONTROL TETHER ORBIT

In low orbit, as an electrically conductive tether passes through Earth's magnetic field, an electron current is induced to flow toward Earth (*left*). This current in turn experiences a force from the Earth's field that is opposite the tether's direction of motion. That produces drag, decreasing the tether's energy and lowering its orbit.

Alternatively, reversing the direction of the tether current (using a solar panel or other power source) would reverse the direction of the force that the tether experiences (*right*). In this case, the force would be in the same direction as the tether system's motion, increasing its energy and raising its orbital altitude.



EXPERIENCING DRAG

Force is in the opposite direction to the tether's motion, lowering its altitude

GENERATING THRUST

Force is in the same direction as the tether's motion, raising its altitude

ALFRED T. KAMAJIAN

er causes the two satellites to act as a single system. The gravity and centrifugal forces still balance at the center of mass, halfway between the satellites, but they no longer balance at the satellites themselves. At the outer satellite, the gravity force will be weaker and the centrifugal force stronger; a net force will thus push the satellite outward. The opposite situation occurs at the inner satellite, which is pulled inward.

What is happening is that the lower satellite, which orbits faster, tows its companion along like an orbital water-skier. The outer satellite thereby gains momentum at the expense of the lower one, causing its orbit to expand and that of the lower one to contract. As the satellites pull away from each other, they keep the tether taut. Nonconductive tethers are typically made of light, strong materials such as Kevlar (a carbon fiber) or Spectra (a high-strength polyethylene). Tensions are fairly low, typically from one half to five kilograms for nonrevolving tether systems.

The only equilibrium position of the system is with the tether aligned along the radial direction, called the local vertical. Every time the system tilts away from that configuration, a torque develops that pulls it back and makes it swing like a pendulum. This type of stabilization was used in the Earth-observing satellite GEOS-3 in 1975 to keep the satellite, equipped with a rigid boom several meters long, oriented toward Earth.

Researchers refer to the force imbalance between the two masses as the gravity gradient. Passengers would perceive it as mild gravity pulling them away from Earth on the outer satellite and toward Earth on the inner. In low Earth orbit (LEO, 200 to 2,000 kilometers), a 50-kilometer tether would provide about 0.01 *g* (1 percent of the gravity at Earth's surface). Astronauts would not be able to walk around: a person cannot get sufficient traction at less than 0.1 *g*. But for many purposes (tool use, showers, settling liquids), having a definitive "up" and "down" would obviously be superior to a completely weightless environment. And unlike other techniques for creating artificial gravity, this method does not require that the satellites revolve around each other [*see illustration on opposite page*].

THE AUTHORS

ENRICO LORENZINI and *JUAN SANMARTÍN* have worked together for a decade on tether projects. Lorenzini is a space scientist at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Mass., where, since 1995, he has led the research group of the late pioneers of space tethers Mario Grossi and Giuseppe Colombo. In 1980 he received his doctorate in aeronautics from the University of Pisa in Italy. Sanmartín has been professor of physics at the Polytechnic University of Madrid in Spain since 1974. Before that, he worked at Princeton University and the Massachusetts Institute of Technology. He has doctoral degrees from the University of Colorado and the Polytechnic University of Madrid.

An EDT, employing aluminum, copper or another conductor in the tether cable, offers additional advantages. For one, it serves as an electrical generator: when a conductor moves through a magnetic field, charged particles in the conductor experience an electrodynamic force perpendicular to both the direction of motion and the magnetic field. So if a tether is moving from west to east through Earth's northward-pointing magnetic field, electrons will be induced to flow down the tether [*see illustration on preceding page*].

The tether exchanges electrons with the ionosphere, a region of the atmosphere in which high-energy solar radiation strips electrons from atoms, creating a jumble of electrons and ions, called a plasma. The tether collects free electrons at one end (the anode, or positively charged electron attractor) and ejects them at the opposite end (the cathode, or negatively charged electron emitter). The electrically conductive ionosphere serves to complete the circuit, and the result is a steady current that can be tapped to use for onboard power. As a practical matter, in LEO a 20-kilometer tether with a suitable anode design could produce up to 40 kilowatts of power, sufficient to run manned research facilities.

That capability has been recognized since the 1970s, when Mario Grossi of the Harvard-Smithsonian Center for Astrophysics and Giuseppe Colombo of the University of Padua in Italy were the first to conduct research on EDTs. As many as 16 experimental missions have flown in space using either electrically conductive or nonconductive tethers [*see box on page 57*].

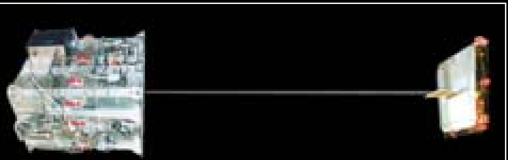
In these early electrodynamic tether systems, a Teflon sleeve fully insulated the conductive part of the tether from the ionosphere, and the anode was either a large conductive sphere or an equivalent configuration to gather electrons. Such anodes, however, turned out to be relatively inefficient collectors. In the 1990s, for example, NASA and the Italian Space Agency jointly launched two versions of the 20-kilometer Tethered Satellite System (TSS). The TSS collected electrons using a metal sphere the size of a beach ball and convincingly demonstrated electrodynamic power generation in space. Despite those positive results, however, researchers discovered a difficulty that must be overcome before EDTs can be put to practical use. A negative net charge develops around a large spherical anode, impeding the flow of incoming electrons much as a single exit door creates a pileup of people when a crowd rushes to leave a room.

One of us (Sanmartín) and his colleagues introduced the bare-tether concept to solve this problem. Left mostly uninsu-

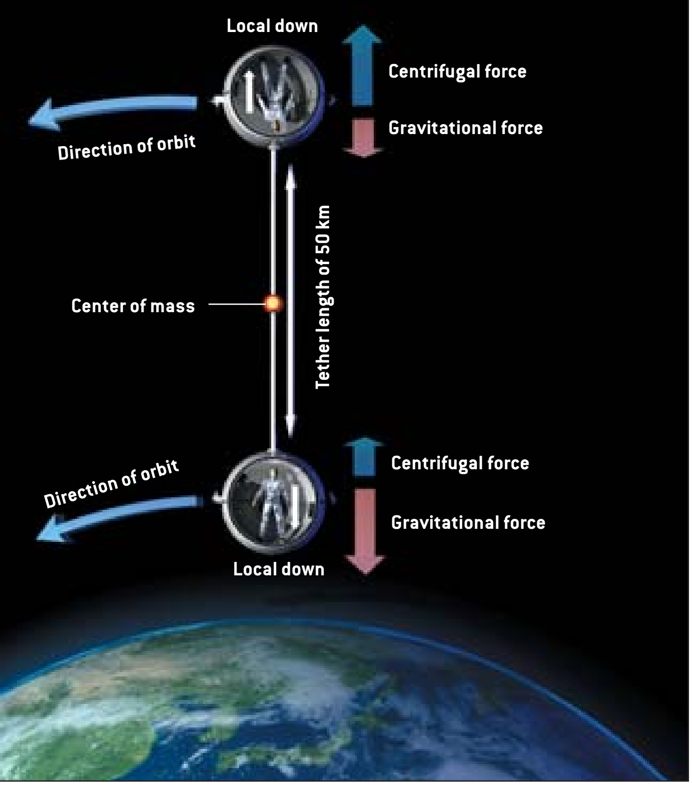
Visionaries imagined using space tethers as space elevators that whisked *people from surface to orbit.*

ARTIFICIAL GRAVITY FROM A TETHER

For any object in a stable orbit, the outward-pushing centrifugal force is exactly balanced by the inward-pulling gravitational force. In a tether system, all forces balance at the system's center of mass. But at the outer sphere, the centrifugal force is slightly larger than the gravitational force. As a result, a passenger would feel a slight "downward" force away from Earth—a form of artificial gravity (local down). The situation is precisely reversed for the inner sphere. For a system with a 50-kilometer-long tether, the force would be about 1/100 the magnitude of Earth's gravity. The force is approximately proportional to the tether length.



COMPOSITE PHOTOGRAPH of an actual tether system, called ATEx, shown in its semideployed state.



lated, the tether itself collects electrons over kilometers of its length rather than just at the tip. The tether benefits further from its thin, cylindrical geometry: electrons do not have to bunch up at one anode point, where their collective negative charge inhibits the arrival of more electrons. It need not be a round wire; a thin tape would collect the same current but would be much lighter.

A Nearly Free Lunch

ALL EDTS SHARE an advantage: they can reduce or increase their velocity while in orbit by exploiting a fundamental principle of electromagnetism. A magnetic field exerts a force on a current-carrying wire according to the familiar "right-hand rule." Thus, for an EDT in eastward LEO, in which the electrons flow from top to bottom of the tether, the force is opposite to the direction of motion. The EDT experiences a resistance akin to air drag, which in turn lowers the tether system's orbit.

That may not seem like a desirable feature. But it is extremely attractive to planners concerned with sweeping up the large amount of space junk that now circles the planet in the form of dead satellites and spent upper stages of rockets. Indeed, the problem has been one of the motivations behind the development of tethers by NASA, universities and small companies. At present, LEO is littered with several thousands of such objects, about 1,500 of which have a mass of more than 100 kilograms. Eventually atmospheric drag removes them from orbit by lowering their altitudes until they burn up on reentry into the dense lower atmosphere. Typically objects at an orbital altitude of 200 kilometers decay in several days, those at 400 kilometers in several months, and those at 1,000 kilometers in about 2,000 years.

If newly launched satellites carried EDTs that could be deployed at the end of their lifetimes, or if a robot manipulator could capture debris and carry it to an orbiting tether system, the drag effect could be used to speed up the reentry timetable [*see illustration on next page*]. Conversely, reversing the direction of the current in an EDT in low Earth orbit (by using a photovoltaic array or other power supply) would produce the opposite effect. The tether system would experience a force in its direction of motion, yielding thrust instead of drag and raising its orbit. Propulsive EDTs could thus serve as space tugs to move payloads in LEO to a higher orbit or to counteract orbital decay. Recall the International Space Station's high-cost boost problem. If the ISS had employed an electrodynamic tether drawing 10 percent of the station power, it would need only 17 tons of propellant (as opposed to 77 in the current design) to avoid orbital decay; more power would nearly eliminate the need for propellant. Also, switching on a propulsive EDT at the right time along the orbit can produce lateral forces useful for changing the inclination of any spacecraft in orbit—an operation that requires a large amount of fuel when it is carried out with chemical thrusters.

Of course, conservation of energy demands that there is no "free lunch." For instance, power is generated only at the ex-

ALFRED T. KAMAJIAN; COURTESY OF THE NAVAL RESEARCH LABORATORY pense of the satellite's altitude, which was originally achieved by expending energy in rocket engines. So it may seem at first glance as if EDTs merely exchange one kind of energy for another in a rather pointless exercise. In drawing power from the tether, the satellite would descend and require reboosting. A fuel cell, in contrast, converts fuel into electricity directly. So why bother?

The answer is that the tether system is potentially more efficient, however paradoxical it may appear. The combination tether/rocket can generate more electrical power than a fuel cell can because the cell does not profit from the orbital energy of its fuel, whereas the tether/rocket does. In an EDT, the electrical power produced is the rate of work done by the magnetic drag—that is, the magnitude of the drag force times the velocity of the satellite (relative to the magnetized ionosphere), which is about 7.5 kilometers per second in LEO. By comparison, the chemical power generated by a rocket equals one half the thrust times the exhaust velocity. A mixture of liquid hydrogen and liquid oxygen produces an exhaust with a speed as high as five kilometers per second. In practical terms, therefore, a tether/rocket combination could generate three times as much electrical power as the chemical reaction alone produces. A fuel cell, which also uses hydrogen and oxygen, has no such advantage.

The combination tether/rocket might consume substantially less fuel than a fuel cell producing equal power. The tradeoff is that the tether is heavier than the fuel cell. Thus, use of a tether to generate power will result in overall savings only for a period longer than five to ten days.

Tethers, by Jove

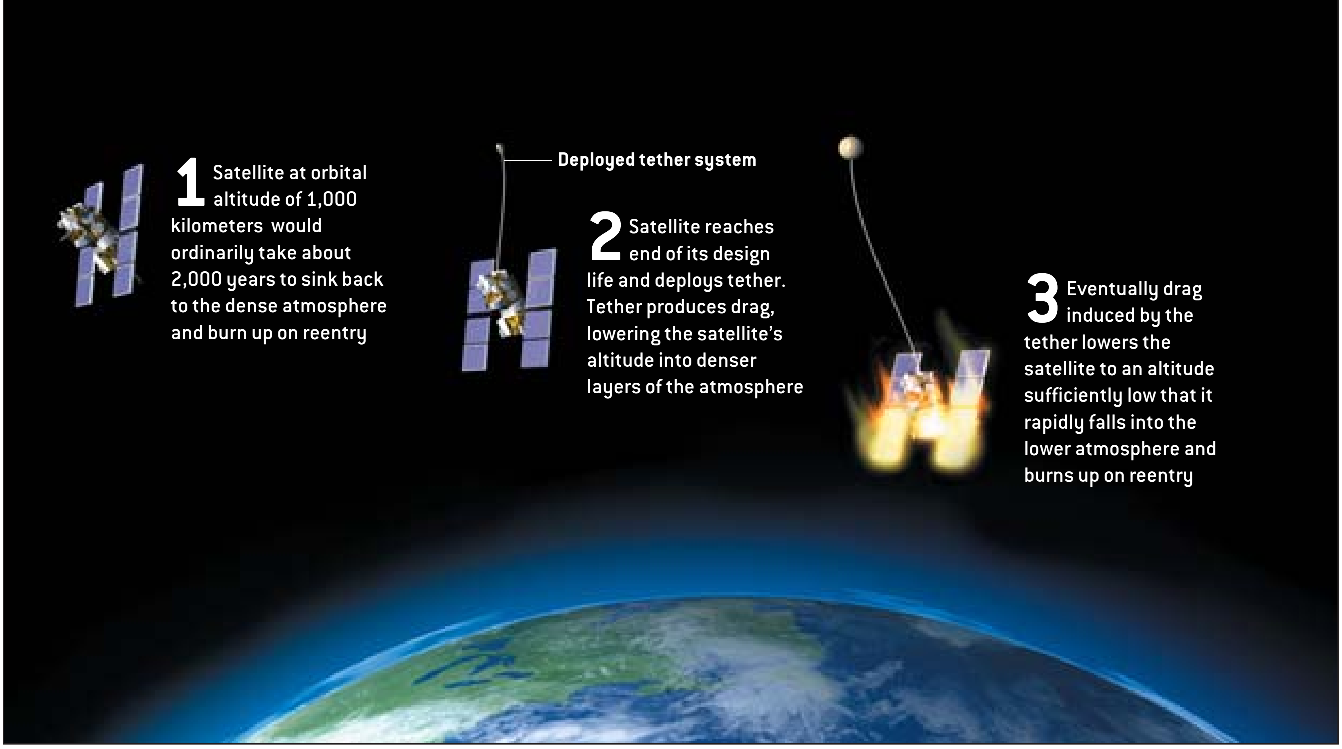
IN CERTAIN CIRCUMSTANCES, such as a mission to explore Jupiter and its moons, tether systems have further advantages. By exploiting the giant planet's physical peculiarities, a tether system could eliminate the need for enormous amounts of fuel. Like Earth, Jupiter has a magnetized ionosphere that rotates with the planet. Unlike Earth, its ionosphere persists beyond the stationary orbit—the altitude at which a given object remains above the same location on the planet's surface. For Earth, that is about 35,800 kilometers; for Jupiter, about 88,500 kilometers above the cloud tops.

In a Jovian stationary orbit, a spacecraft goes around the planet at the same speed as the ionosphere. So if the spacecraft descends below stationary altitude, where the speed of the magnetized plasma is lower than the speed of the spacecraft, the natural output of an EDT is a drag force, along with usable electrical power from the tether current. Alternatively, above the stationary orbit, where the magnetized plasma moves faster than the spacecraft, the natural result is thrust and usable electrical power.

USING TETHERS TO REMOVE OBJECTS FROM ORBIT

The region of low Earth orbit—from 200 to 2,000 kilometers above the surface—has become littered with tens of thousands of objects, including defunct satellites, rocket motors, explosion debris and miscellaneous hardware.

It takes decades to centuries for these objects to sink into the lower atmosphere, where they are incinerated by air friction. Deploying tethers on newly launched spacecraft would provide a simple and low-cost way to speed up that timetable.



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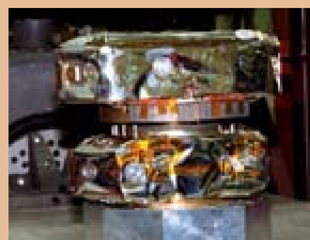
TETHERED MISSIONS

Researchers have launched experimental tether systems for decades, with varying degrees of success. Sometimes the tethers could not extend to their full lengths. But even problematic flights have confirmed the capabilities of tether systems and led to numerous design improvements. Missions that used electrodynamic tethers are indicated in brown.

NAME	DATE	ORBIT	LENGTH	AGENCY
Gemini 11	1967	LEO	30 m	NASA
Gemini 12	1967	LEO	30 m	NASA
H-9M-69	1980	Suborbital	< 500 m	NASA
S-520-2	1981	Suborbital	< 500 m	NASA
Charge-1	1983	Suborbital	500 m	NASA/Japanese ISAS
Charge-2	1984	Suborbital	500 m	NASA/Japanese ISAS
Oedipus-A	1989	Suborbital	958 m	Canadian NRC/NASA
Charge-2B	1992	Suborbital	500 m	NASA/Japanese ISAS
TSS-1	1992	LEO	< 500 m	NASA/Italian Space Agency
SEDS-1	1993	LEO	20 km	NASA
PMG	1993	LEO	500 m	NASA
SEDS-2	1994	LEO	20 km	NASA
Oedipus-C	1995	Suborbital	1 km	Canadian NRC/NASA
TSS-1R	1996	LEO	19.6 km	NASA/Italian Space Agency
TiPS	1996	LEO	4 km	NRO/NRL
ATEx	1999	LEO	6 km	NRL

ATEx



TiPS

Again, this might appear to be a free-lunch scenario. But it is not. The energy is taken from the planet's rotation in both cases. Jupiter's collective momentum, however, is so vast that the tiny amount expended on the spacecraft is negligible.

According to the principles of orbital dynamics, the most efficient places to apply drag or thrust are the points in the orbit nearest (periapsis) and farthest (apoapsis) from Jupiter. The natural force will be drag if the point lies inside the stationary orbit and thrust if it lies outside. Assume that a tether-bearing spacecraft would approach Jupiter with a relative velocity of about six kilometers per second. If drag were not applied, the spacecraft would fly past Jupiter. But if the tether were turned on as the spacecraft came inside the stationary orbit, it could brake the motion just enough to put the spacecraft in an elongated, highly eccentric ellipse around Jupiter. Capture into such an orbit requires reducing the velocity by only hundreds of meters per second. A tether tens of kilometers long would suffice.

As the spacecraft went around and around Jupiter, mission controllers would turn on the tether near periapsis to produce drag (and usable power) and turn it off elsewhere. That gradually would reduce the orbit from an elongated ellipse to smaller, progressively more circular shapes. The spacecraft would then require only modest electrodynamic forces to visit each of the four largest moons of Jupiter, from the outermost (Callisto) to the innermost (Io). With Callisto's orbital period of about half a month, the entire sequence could take less than a year.

To return, controllers would reverse the process. They would first switch on the EDT at apoapsis, which lies outside the stationary orbit, to produce thrust and power. The repeated thrust applications at apoapsis would raise periapsis from inside to outside the stationary orbit. Now thrust could be generated (for "free" again) at periapsis, progressively increasing the altitude of apoapsis. A final push could boost the spacecraft out of orbit for transfer back to Earth. Tapping Jupiter's rotation would provide all the energy for these maneuvers as well as generate usable power. By reducing drastically the fuel and power requirements, the tether would greatly cut the cost of a mission.

The technology of space tethers has matured tremendously in the past 30 years. But it still faces several challenges before EDTs can be put to practical use in orbit around Earth, Jupiter or elsewhere. Designers will have to devise ways to protect tethers from the effects of the high electrical potential between the tether and the ionosphere as well as from the slow degradation of materials in space. And they must learn to control the various vibrations that arise in electrodynamic tether systems. These obstacles are not insuperable, however, and many scientists expect to see tethers doing real work in orbit in the not so distant future. SA

MORE TO EXPLORE

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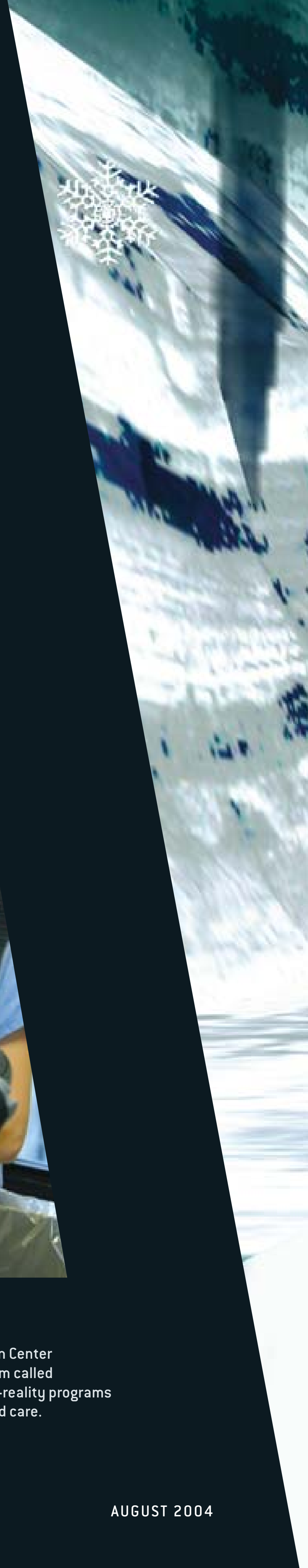


VIRTUAL-REALITY THERAPY

Patients can get relief from pain or overcome their phobias by immersing themselves in computer-generated worlds

BY HUNTER G. HOFFMAN

BURN PATIENT participates in a virtual-reality program to relieve the pain of his wound care at Harborview Burn Center in Seattle (*above*). Wearing a headset and manipulating a joystick, the patient maneuvers through the program called SnowWorld (*right*), which was specifically designed to ease the pain of burn victims. Studies show that virtual-reality programs are more effective than ordinary video games in distracting patients from the often excruciating pain of wound care.

In the science-fiction thriller *The Matrix,* the heroes "plugged in" to a virtual world. While their bodies rested in reclining chairs, their minds fought martial-arts battles, dodged bullets and drove motorcycles in an elaborately constructed software program. This cardinal virtue of virtual reality—the ability to give users the sense that they are "somewhere else"—can be of great value in a medical setting. Researchers are finding that some of the best applications of the software focus on therapy rather than entertainment. In essence, virtual reality can ease pain, both physical and psychological.

For the past several years, I have worked with David R. Patterson, a pain expert at the University of Washington School of Medicine, to determine whether severely burned patients, who often face unbearable pain, can relieve their discomfort by engaging in a virtual-reality program during wound treatment. The results have been so promising that a few hospitals are now preparing to explore the use of virtual reality as a tool for pain control. In other projects, my colleagues and I are using virtual-reality applications to help phobic patients overcome their irrational fear of spiders and to treat posttraumatic stress disorder (PTSD) in survivors of terrorist attacks.

At least two software companies are already leasing virtual-reality programs and equipment to psychologists for phobia treatment in their offices. And the Virtual Reality Medical Center, a chain of clinics in California, has used similar programs to successfully treat more than 300 patients suffering from phobias and anxiety disorders. Although researchers must conduct more studies to gauge the effectiveness of these applications, it seems clear that virtual therapy offers some very real benefits.

SpiderWorld and SnowWorld

FEW EXPERIENCES are more intense than the pain associated with severe burn injuries. After surviving the initial trauma, burn patients must endure a long journey of healing that is often as painful as the original injury itself. Daily wound care—the gentle cleaning and removal of dead tissue to prevent infection—can be so excruciating that even the aggressive use of opioids (morphine-related analgesics) cannot control the pain. The patient's healing skin must be stretched to preserve its elasticity, to reduce muscle atrophy and to prevent the need for further skin grafts. At these times, most patients—and especially children—would love to transport their minds somewhere else while doctors and nurses treat their wounds. Working with the staff at Harborview Burn Center in Seattle, Patterson and I set out in 1996 to determine whether immersive virtual-reality techniques could be used to distract patients from their pain. The team members include Sam R. Sharar, Mark Jensen and Rob Sweet of the University of Washington School of Medicine, Gretchen J. Carrougher of Harborview Burn Center and Thomas Furness of the University of Washington Human Interface Technology Laboratory (HITLab).

Pain has a strong psychological component. The same incoming pain signal can be interpreted as more or less painful depending on what the patient is thinking. In addition to influencing the way patients interpret such signals, psychological factors can even influence the amount of pain signals allowed to enter the brain's cortex. Neurophysiologists Ronald Melzack and Patrick D. Wall developed this "gate control" theory of pain in the 1960s [see "The Tragedy of Needless Pain," by Ronald Melzack; SCIENTIFIC AMERICAN, February 1990].

Introducing a distraction—for example, by having the patient listen to music—has long been known to help reduce pain for some people. Because virtual reality is a uniquely effective new form of distraction, it makes an ideal candidate for pain control. To test this notion, we studied two teenage boys who had suffered gasoline burns. The first patient had a severe burn on his leg; the second had deep burns covering one third of his body, including his face, neck, back, arms, hands and legs. Both had received skin-graft surgery and staples to hold the grafts in place.

We performed the study during the removal of the staples from the skin grafts.

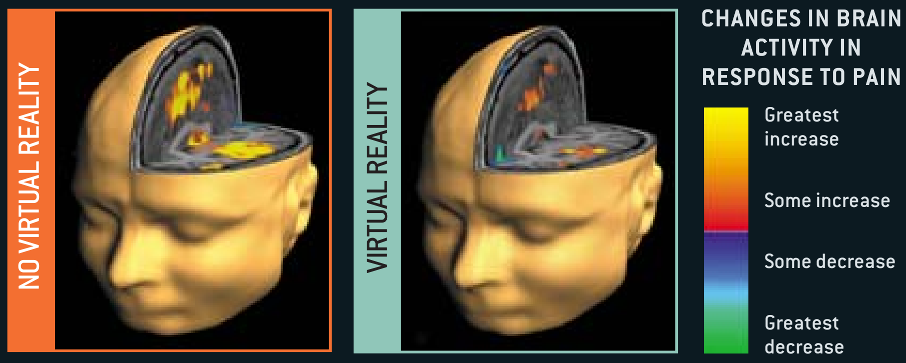
Overview/*Virtual-Reality Therapy*

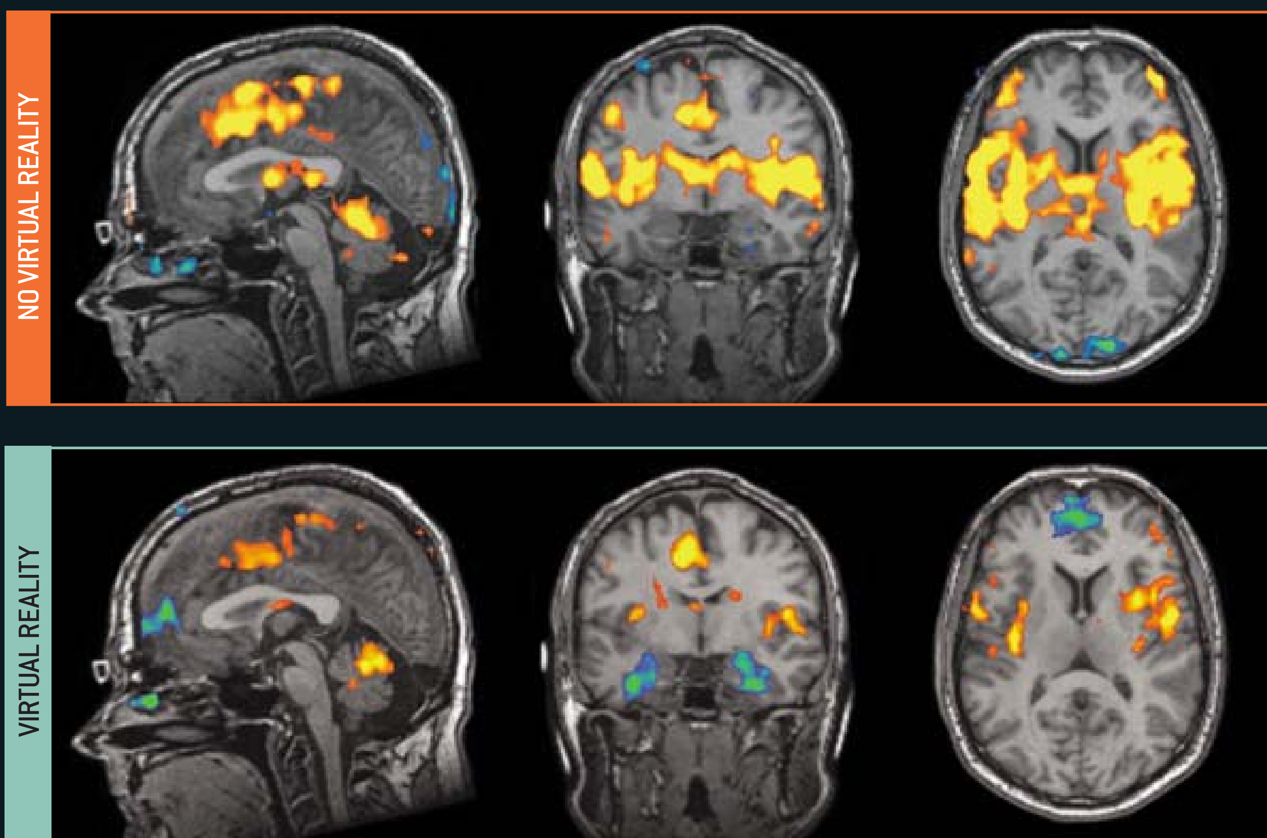
- One of the best ways to alleviate pain is to introduce a distraction. Because virtual reality immerses users in a three-dimensional computer-generated world, it is uniquely suited to distracting patients from their pain.
- Burn patients undergoing wound care report that their pain drops dramatically when they engage in virtual-reality programs. Functional magnetic resonance imaging shows that virtual reality actually reduces the amount of pain-related activity in the brain.
- Virtual-reality programs can also help phobic patients overcome their fear of spiders, heights, flying or public speaking. A specially designed program is now being used to treat post-traumatic stress disorder in survivors of the September 11 attacks.

HUNTER G. HOFFMAN (*burn patient*); STEPHEN DAGADAKIS *University of Washington* (*SnowWorld*); © HUNTER G. HOFFMAN (*preceding pages*)

PAIN-RELATED BRAIN ACTIVITY

When healthy volunteers received pain stimuli, functional magnetic resonance imaging showed large increases in activity in several regions of the brain that are known to be involved in the perception of pain (*near right* and *below*). But when the volunteers engaged in a virtual-reality program during the stimuli, the pain-related activity subsided (*far right* and *bottom*).





TODD RICHARDS AND ARIC BILLS *University of Washington;* © HUNTER G. HOFFMAN

The boys received their usual opioid medication before treatment. In addition, each teenager spent part of the treatment session immersed in a virtual-reality program and an equal amount of time playing a popular Nintendo video game (either Wave Race 64, a jet-ski racing game, or Mario Kart 64, a race-car game). The virtual-reality program, called SpiderWorld, had originally been developed as a tool to overcome spider phobias; we used it for this investigation because it was the most distracting program available at the time and because we knew it would not induce nausea. Wearing a stereoscopic, position-tracked headset that presented three-dimensional computer graphics, the patients experienced the illusion of wandering through a kitchen, complete with countertops, a window and cabinets that could be opened. An image of a tarantula was set inside the virtual kitchen; the illusion was enhanced by suspending a furry spider toy with wiggly legs above the patient's bed so that he could actually feel the virtual spider.

Both teenagers reported severe to excruciating pain while they were playing the Nintendo games but noted large drops in pain while immersed in SpiderWorld. (They rated the pain on a zero to 100 scale immediately after each treatment session.) Although Nintendo can hold a healthy player's attention for a long time, the illusion of going inside the two-dimensional video game was found

Virtual reality is not just changing the way patients interpret incoming pain signals; the programs actually reduce the amount of pain-related brain activity.

to be much weaker than the illusion of going into virtual reality. A follow-up study involving 12 patients at Harborview Burn Center confirmed the results: patients using traditional pain control (opioids alone) said the pain was more than twice as severe compared with when they were inside SpiderWorld.

Why is virtual reality so effective in alleviating pain? Human attention has been likened to a spotlight, allowing us to select some information to process and to ignore everything else, because there is a limit to how many sources of information we can handle at one time. While a patient is engaged in a virtual-reality program, the spotlight of his or her attention is no longer focused on the wound and the pain but drawn into the virtual world. Because less attention is available to process incoming pain signals, patients often experience dramatic drops in how much pain they feel and spend much less time thinking about their pain during wound care.

To increase the effectiveness of the virtual therapy, our team created SnowWorld, a program specifically customized for use with burn patients during wound care. Developed with funding from Microsoft co-founder Paul G. Allen and the National Institutes of Health, SnowWorld produces the illusion of flying through an icy canyon with a frigid river and waterfall, as snowflakes drift down [*see illustration on pages 58 and 59*]. Because patients often report that they are reliving their original burn experience during wound care, we designed a glacial landscape to help put out the fire. As patients glide through the virtual canyon, they can shoot snowballs at snowmen, igloos, robots and penguins standing on narrow ice shelves or floating in the river. When hit by a snowball, the snowmen and igloos disappear in a puff of powder, the penguins flip upside down with a quack, and the robots collapse into a heap of metal.

More recent research has shown that the benefits of virtual-reality therapy are not limited to burn patients. We conducted a study involving 22 healthy volunteers, each of whom had a blood pressure cuff tightly wrapped around one arm for 10 minutes. Every two minutes the subjects rated the pain from the cuff; as expected, the discomfort rose as the session wore on. But during the last two minutes, each of the subjects participated in two brief virtual-reality programs, SpiderWorld and ChocolateWorld. (In ChocolateWorld, users see a virtual chocolate bar that is linked through a position sensor to an actual candy bar; as you eat the real chocolate bar, bite marks appear on the virtual bar as well.) The subjects reported that their pain dropped dramatically during the virtual-reality session.

What is more, improving the quality of the virtual-reality system increases the amount of pain reduction. In another study, 39 healthy volunteers received a thermal pain stimulus—delivered by an electrically heated element applied to the right foot, at a preapproved temperature individually tailored to each participant—for 30 seconds. During this stimulus, 20 of the subjects experienced the fully interactive version of SnowWorld with a high-quality headset, sound effects and head tracking. The other 19 subjects saw a stripped-down program with a low-quality, see-through helmet, no sound effects, no head tracking and no ability to shoot snowballs. We found a significant positive correlation between the potency of the illusion—how strongly the subjects felt they were immersed in the virtual world—and the alleviation of their pain.

Seeing Pain in the Brain

OF COURSE, all these studies relied on the subjective evaluation of the pain by the patients. As a stricter test of whether virtual reality reduces pain, I set out with my colleagues at the University of Washington—including Todd L. Richards, Aric R. Bills, Barbara A. Coda and Sam Sharar—to measure pain-related brain activity us-

VIRTUAL-REALITY PROGRAM re-creating a bus bombing is designed to treat post-traumatic stress disorder in survivors of terrorist attacks in Israel and Spain. By gradually exposing the survivors to realistic images and sounds of a bus bombing [*three screen shots are shown here*], the program helps them to process and eventually reduce the debilitating emotions associated with the traumatic event.

ARI HOLLANDER *Imprint Interactive Technology LLC*; © HUNTER G. HOFFMAN ing functional magnetic resonance imaging (fMRI). Healthy volunteers underwent a brain scan while receiving brief pain stimulation through an electrically heated element applied to the foot. When the volunteers received the thermal stimuli without the distraction of virtual reality, they reported severe pain intensity and unpleasantness and spent most of the time thinking about their pain. And, as expected, their fMRI scans showed a large increase in pain-related activity in five regions of the brain that are known to be involved in the perception of pain: the insula, the thalamus, the primary and secondary somatosensory cortex, and the affective division of the anterior cingulate cortex [*see illustration on page 61*].

Creating virtual-reality goggles that could be placed inside the fMRI machine was a challenge. We had to develop a fiber-optic headset constructed of nonferrous, nonconducting materials that would not be affected by the powerful magnetic fields inside the fMRI tube. But the payoff was gratifying: we found that when the volunteers engaged in SnowWorld during the thermal stimuli, the pain-related activity in their brains decreased significantly (and they also reported large reductions in subjective pain ratings). The fMRI results suggest that virtual reality is not just changing the way patients interpret incoming pain signals; the programs actually reduce the amount of pain-related brain activity.

Encouraged by our results, two large regional burn centers—the William Randolph Hearst Burn Center at New York Weill Cornell Medical Center and Shriners Hospital for Children in Galveston, Tex.—are both making preparations to explore the use of SnowWorld for pain control during wound care for severe burns. Furthermore, the Hearst Burn Center, directed by Roger W. Yurt, is helping to fund the development of a new upgrade, SuperSnowWorld, which will feature lifelike human avatars that will interact with the patient. SuperSnowWorld will allow two people to enter the same virtual world; for example, a burn patient and his mother would be able to see each other's avatars and work together to defeat monstrous virtual insects and animated sea creatures rising from the icy river. By maximizing the illusion and interactivity, the program will help patients focus their attention on the virtual world during particularly long and painful wound care sessions. Now being built by Ari Hollander, an affiliate of HITLab, SuperSnowWorld will be offered to medical centers free of charge by the Hearst and Harborview burn centers.

Virtual-reality analgesia also has the potential to reduce patient discomfort during other medical procedures. Bruce Thomas and Emily Steele of the University of South Australia have found that virtual reality can alleviate pain in cerebral palsy patients during physical therapy after muscle and tendon surgery. (Aimed at improving the patient's ability to walk, this therapy involves exercises to stretch and strengthen the leg muscles.) Our team at the University of Washington is exploring the clinical use of virtual reality during a painful urological procedure called a rigid cystoscopy. And we have conducted a study showing that virtual reality can even relieve the pain and fear of dental work.

FEAR OF PUBLIC SPEAKING can be treated using a virtual-reality program developed by Virtually Better, a software company based in Decatur, Ga., that leases its programs to psychologists and psychiatrists. Ken Graap, the company's chief executive, practices a speech in front of a virtual audience, shown on his headset and on the computer monitor.

Fighting Fear

ANOTHER THERAPEUTIC application of virtual reality is combating phobias by exposing patients to graphic simulations of their greatest fears. This form of therapy was introduced in the 1990s by Barbara O. Rothbaum of Emory University and Larry F. Hodges, now at the University of North Carolina at Charlotte, for treating fear of heights, fear of flying in airplanes, fear of public speaking, and chronic post-traumatic stress disorder in Vietnam War veterans. Like the pain-control programs, exposure therapy helps to change the way people think, behave and interpret information.

Working with Albert Carlin of HIT-

THE AUTHOR

HUNTER G. HOFFMAN is director of the Virtual Reality Analgesia Research Center at the University of Washington Human Interface Technology Laboratory (HITLab) in Seattle. He is also an affiliate faculty member in the departments of radiology and psychology at the University of Washington School of Medicine. He joined the HITLab in 1993 after earning his Ph.D. in cognitive psychology at the University of Washington. To maximize the effectiveness of virtual reality in reducing physical and psychological suffering, he is exploring ways to enhance the illusion of going inside a computer-generated virtual world.

ERIK S. LESSER

Lab and Azucena Garcia-Palacios of Jaume I University in Spain (a HITLab affiliate), our team has shown that virtual-reality exposure therapy is very effective for reducing spider phobia. Our first spider-phobia patient, nicknamed Miss Muffet, had suffered from this anxiety disorder for nearly 20 years and had acquired a number of obsessive-compulsive behaviors. She routinely fumigated her car with smoke and pesticides to get rid of spiders. Every night she sealed all her bedroom windows with duct tape after scanning the room for spiders. She searched for the arachnids wherever she went and avoided walkways where she might find one. After washing her clothes, she immediately sealed them inside a plastic bag to make sure they remained free of spiders. Over the years her condition grew worse. When her fear made her hesitant to leave home, she finally sought therapy.

Like other kinds of exposure therapy, the virtual-reality treatment involves introducing the phobic person to the feared object or situation a little at a time. Bit by bit the fear decreases, and the patient becomes more comfortable. In our first sessions, the patient sees a virtual tarantula in a virtual kitchen and approaches as close as possible to the arachnid while using a handheld joystick to navigate through the three-dimensional scene. The goal is to come within arm's reach of the virtual spider.

During the following sessions, the participant wears a glove that tracks the position of his or her hand, enabling the software to create an image of a hand—the cyberhand—that can move through the virtual kitchen. The patient maneuvers the cyberhand to touch the virtual spider, which is programmed to respond by making a brief noise and fleeing a few inches. The patient then picks up a virtual vase with the cyberhand; when the patient lets go, the vase remains in midair, but an animated spider with wiggling legs comes out. The spider drifts to the floor of the virtual kitchen, accompanied by a brief sound effect from the classic horror movie *Psycho*. Participants repeat each task until they report little anxiety. Then they move on to the next challenge. The final therapy sessions add tactile feedback to the virtual experience: a toy spider with an electromagnetic position sensor is suspended in front of the patient, allowing him or her to feel the furry object while touching the virtual spider with the cyberhand.

After only 10 one-hour sessions, Miss Muffet's fear of spiders was greatly reduced, and her obsessive-compulsive behaviors also went away. Her success was unusually dramatic: after treatment, she was able to hold a live tarantula (which crawled partway up her arm) for several minutes with little anxiety. In a subsequent controlled study of 23 patients diagnosed with clinical phobia, 83 percent reported a significant decrease in their fear of spiders. Before treatment, these patients could not go within 10 feet of a caged tarantula without high anxiety; af-

SPIDERWORLD is a virtual-reality program designed to help phobic patients overcome their fear of spiders. The patient wears a headset that shows a virtual tarantula (*screen shot from program is shown in background*). To provide tactile feedback, the system tracks the positions of a toy spider (*suspended by the author, at left*) and the patient's hand, allowing her to "touch" the virtual creature.

BENJAMIN BENSCHNEIDER *Seattle Times*

ter the virtual-reality therapy, most of them could walk right up to the cage and touch its lid with only moderate anxiety. Some patients could even remove the lid.

Similar programs can be incorporated into the treatment of a more serious psychological problem: post-traumatic stress disorder. The symptoms of PTSD include flashbacks of a traumatic event, intense reactions to anything symbolizing or resembling the event, avoidance behaviors, emotional numbing, and irritability. It is a debilitating disorder that affects the patient's social life and job performance and is much more challenging to treat than specific phobias. Cognitive behavioral therapy protocols, such as the prolonged exposure therapy developed by University of Pennsylvania psychologist Edna Foa, have a high success rate for patients with PTSD. The exposure therapy is thought to work by helping patients process and eventually reduce the emotions associated with the memories of the traumatic event. The therapist gradually exposes the patient to stimuli that activate these emotions and teaches the patient how to manage the unwanted responses.

Researchers are now exploring whether virtual-reality programs can be used to standardize the therapy and improve the outcome for patients, especially those who do not respond to traditional methods. JoAnn Difede of Cornell University and I developed a virtual-reality exposure therapy to treat a young woman who was at the World Trade Center during the September 11 attacks and later developed PTSD. During the therapy, the patient put on a virtual-reality helmet that showed virtual jets flying over the towers and crashing into them with animated explosions and sound effects. Although the progress of the therapy was gradual and systematic, the scenes presented by the software in the final sessions were gruesomely realistic, with images of people jumping from the burning buildings and the sounds of sirens and screams. These stimuli can help patients retrieve memories of the event and, with the guidance of a therapist, lower the discomfort of remembering what happened.

Our first patient showed a large and stable reduction in her PTSD symptoms and depression after the virtual-reality sessions. Other patients traumatized by the tower attacks are now being treated with virtual-reality therapy at Weill Cornell Medical College and New York Presbyterian Hospital. I am also collaborating with a team of researchers led by Patrice L. (Tamar) Weiss of Haifa University in Israel and Garcia-Palacios to create a virtual-reality treatment for survivors of terrorist bombings who develop PTSD.

Another therapeutic application of virtual reality is combating phobias by exposing patients to graphic simulations of their greatest fears.

Virtual Reality by the Hour

BECAUSE DOZENS of studies have established the efficacy of virtual-reality therapy for treating specific phobias, this is one of the first medical applications to make the leap to widespread clinical use. Virtually Better, a Decatur, Ga.–based company that was co-founded by virtual-reality pioneers Hodges and Rothbaum, has produced programs designed to treat an array of anxiety disorders, including fear of heights, fear of flying and fear of public speaking. The company is leasing its software to psychologists and psychiatrists for $400 a month, allowing therapists to administer the treatments in their own offices. A Spanish firm called PREVI offers similar programs. Instead of reclining on a couch, patients interactively confront their fears by riding in virtual airplanes or by standing in front of virtual audiences.

In contrast, more research is needed to determine whether virtual reality can enhance the treatment of PTSD. Scientists have not yet completed any randomized, controlled studies testing the effectiveness of virtual-reality therapy for treating the disorder. But some of the leading PTSD experts are beginning to explore the virtues of the technology, and the preliminary results are encouraging.

Large clinical trials are also needed to determine the value of virtual-reality analgesia for burn patients. So far the research has shown that the SnowWorld program poses little risk and few side effects. Because the patients use SnowWorld in addition to traditional opioid medication, the subjects who see no benefit from virtual reality are essentially no worse off than if they did not try it. Virtual reality may eventually help to reduce reliance on opioids and allow more aggressive wound care and physical therapy, which would speed up recovery and cut medical costs. The high-quality virtual-reality systems that we recommend for treating extreme pain are very expensive, but we are optimistic that breakthroughs in display technologies over the next few years will lower the cost of the headsets. Furthermore, patients undergoing less painful procedures, such as dental work, can use cheaper, commercially available systems. (Phobia patients can also use the less expensive headsets.)

The illusions produced by these programs are nowhere near as sophisticated as the world portrayed in the *Matrix* films. Yet virtual reality has matured enough so that it can be used to help people control their pain and overcome their fears and traumatic memories. And as the technology continues to advance, we can expect even more remarkable applications in the years to come. SA

MORE TO EXPLORE

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Virtual Reality Technology. Second edition, with CD-ROM. Grigore C. Burdea and Philippe Coiffet. John Wiley & Sons, 2003.

More information about virtual-reality therapy can be found on the Web at **www.hitl.washington.edu/** and **www.e-therapy.info**

Nuclear Bunker Buster Bombs

ESCAPE OF ATOMIC FALLOUT was the unexpected result of the U.S. Baneberry underground nuclear test in 1970. Buried some 275 meters below the Nevada desert, the 10-kiloton weapon nonetheless released radioactive fallout into the atmosphere. This surface venting testifies to the difficulties involved in containing subterranean detonations.

COURTESY OF NATIONAL NUCLEAR SECURITY ADMINISTRATION, NEVADA SITE OFFICE

By Michael Levi

New burrowing nuclear weapons could destroy subterranean military facilities—but their strategic and tactical utility is questionable

Potential opponents of the U.S. armed forces learned an important lesson during the first Gulf War. As smart bombs rained down with pinpoint precision on Iraqi command centers, weapons storage depots and other facilities, it became clear that fixed military assets on the surface were extremely vulnerable to American aerial assault. To survive, key operational bases and weapons caches would have to be situated underground in fortified concrete bunkers or inside hard-rock mountains.

In the years following Operation Desert Storm, U.S. military strategists debated the best way to destroy such "hardened" and deeply buried targets, knowing full well that attacks on subterranean bunkers or weapons stockpiles would face uncertain chances of success. Worse, they could inadvertently disperse any buried chemical or biological agents into the surrounding areas—with lethal effect.

One solution that defense strategists discussed would be to deploy earth-penetrating nuclear warheads with reduced explosive yields. The specialized munitions would burrow a short way into the ground before detonating, thereby increasing their destructiveness and, it was hoped, reducing the release of radioactive fallout. In principle, the heat and radiation from the explosion could also destroy chemical and biological agents before they could escape from the bunkers to endanger nearby populations. Throughout the 1990s supporters unsuccessfully proposed to build such so-called nuclear "bunker buster" bombs.

Renewed interest in these weapons was revealed, however, in the U.S. Nuclear Posture Review (NPR) of December 2001, a classified defense document leaked to the press a few months afterward. That report advocated study

No matter how deep a BOMB DIGS, it will leave a hole behind it through which FALLOUT CAN ESCAPE.

of new nuclear military technologies to expand the strategic options available to the Pentagon. Under the auspices of the Department of Energy's National Nuclear Security Administration, $6.1 million was spent in 2003 for research on a Robust Nuclear Earth Penetrator (RNEP) bomb, followed by another $7.5 million in 2004. The administration plans to raise these appropriations sharply and spend $484.7 million between 2005 and 2009. At the same time, Congress has approved an Advanced Concepts Initiative, which will explore more exotic—and more controversial—variations on the same theme. To many observers, these substantial spending allocations and this breadth of research suggest that the administration has already tacitly committed to building RNEPs and is actively considering developing other types of nuclear bombs.

The new programs dismay arms control advocates, who argue that the U.S. will squander its leadership in preventing nuclear proliferation and might also provoke other states to pursue similar technologies. In one critique, Senator Edward Kennedy of Massachusetts warned that "a nuclear weapon is not just another item in our arsenal, and it's wrong to treat it like it is." Daryl Kimball, executive director of the Washington, D.C.–based Arms Control Association, declared that "the Bush administration's do-as-I-say, not-as-I-do nuclear weapons policies contradict the U.S.'s NPT [Non-Proliferation Treaty] commitments and jeopardize the future of the treaty." Other critics have derided the concept of small nuclear weapons as "immaculate preemption," unconvinced that even a comparatively small nuclear explosion could yield useful results without leaving an unacceptably nasty mess.

Lost in the frenzied debate over nuclear bunker busters has been adequate discussion of whether the military advantages of these weapons can offset their political and diplomatic liabilities. Nonnuclear alternatives to these technologies may well be able to achieve most, if not all, of the same ends with far less incidental risk—not just political and human, but military as well.

Nukes to the Rescue?

SOME WEAPONS designers have argued that low-yield earth-penetrating nuclear arms, with explosive yields ranging from the equivalent of 10 to 1,000 tons of TNT, would provide unique tactical and strategic capabilities while minimizing unwanted collateral effects—in particular, the atomic fallout typically generated in abundance by more powerful bombs. Shifting from big nuclear devices that burst at the earth's surface to smaller ones that detonate below ground could indeed reduce the radioactive fallout released by a factor of about 20—but it would by no means make the smaller munitions "clean."

This new breed of burrowing nuclear weapons would be more effective against subsurface targets because detonation underground enhances the ground shock a bomb can create. Much of the shock wave produced by a device exploding at or above the earth's surface reflects off the ground-air interface. That rebound sends the shock skyward, away from the buried bunker. If the same-size bomb is set off below the surface, most of the shock propagates directly to the target. Even a small amount of penetration can make an enormous difference in destructive power: a one-kiloton device exploded one meter underground delivers more shock to a buried base or stockpile than a 20-kiloton bomb detonated aboveground.

A shallow subsurface nuclear explosion produces a large crater, obliterating facilities within its radius and any just beyond it where strong stresses rupture the earth. The size of the roughly hemispherical destruction zone that results depends on the yield of the weapon, the detonation depth and the composition of the ground. Hard strata transmit shock waves more efficiently than loose earth. A one-kiloton bomb detonated five meters deep in granite, for example, will demolish well-built bunkers 35 meters underground, whereas a 10-kiloton device exploding under one meter of soil has a destructive radius of only five meters.

A Deadly Rain

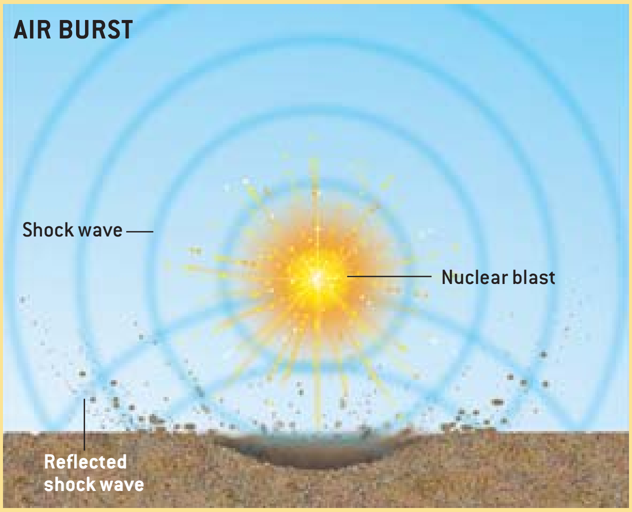
BY DECREASING the explosive power required to terminate a buried target, the use of earth-penetrating nuclear weapons lessens the amount of incidental radioactive fallout. Four scientists from Los Alamos National Laboratory (Bryan L. Fearey, Paul C. White, John St. Ledger and John D. Immele) recently estimated in the journal *Comparative Strategy* that a small nuclear bomb that penetrated the ground 10 meters before exploding could be roughly $\frac{1}{40}$ the size of a bomb detonated at the surface and still achieve its goal. Switching to this downsized bomb

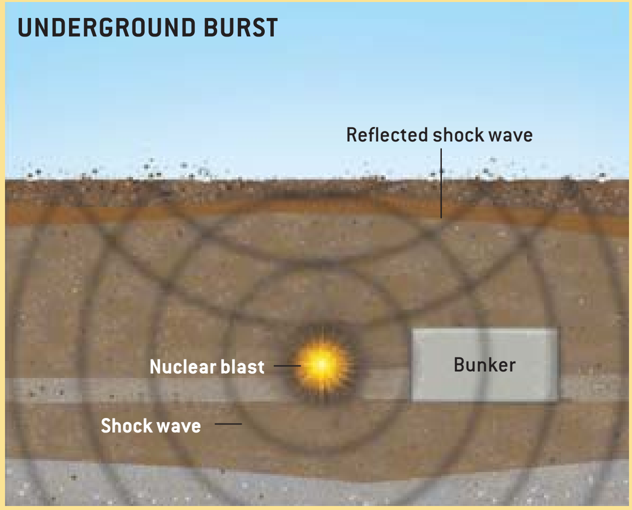
Overview/*Burrowing Bombs*

- Potential military opponents of the U.S. are building fortified underground bunkers and buried caches of weapons of mass destruction to counter the threat of modern bombs.
- The Bush administration is funding research on earth-penetrating nuclear weapons—"bunker-busting" atomic bombs that burrow underground before detonating. The resulting destructive effects would be enhanced, allowing smaller bombs that produce less radioactive fallout to be used.
- Novel nonnuclear bunker-busting technologies may be able to duplicate the practical effects of subsurface atomic explosives and thus avoid their political, strategic and military drawbacks.

THE PHYSICS OF BOMB PLACEMENT

For a bomb that goes off at or near the surface, most of the shock wave rebounds upward from the ground (*left*). The destructive power of a nuclear explosion against an underground target is enhanced manyfold, however, if the bomb is placed below the surface. Most of the resulting shock wave is transmitted directly to a buried target (*right*). As a result, a single-kiloton bomb set off a meter underground would deliver more shock force to a nearby subterranean target than would a 20-kiloton bomb detonated aboveground to that same target. In any realistic scenario, after the shock wave crushes the target bunker, the expanding cavity would breach the surface, resulting in the release of radioactive fallout.





KENT SNODGRASS *Precision Graphics*

would reduce the area affected by radioactive fallout by a factor of about 10.

But is that reduction sufficient to contemplate deploying earth-penetrating nuclear bombs? According to the Congressional Office of Technology Assessment's report "The Containment of Underground Nuclear Explosions," fully containing the fallout from a one-kiloton nuclear weapon requires detonating it 90 meters underground in a carefully sealed cavity. Today's best penetrator missiles can reach a depth of only about six meters in dry rock, and as Robert W. Nelson of Princeton University has argued in *Physics Today*, limits on the strengths of materials suggest that 20 meters might be a theoretical maximum. These depths might be further extended by using novel penetrating techniques rather than simple missiles (as described below). But no matter how deep a bomb digs, it will leave a hole behind it through which fallout can escape. These figures leave little doubt that use of a nuclear bunker buster would spread fallout; in an urban area, a kiloton-size bomb could kill tens of thousands.

Downsized weapons would probably offer greater utility in less populated areas. Consider a one-kiloton bunker buster bomb set off at relatively shallow depth—less than 10 meters—in wind conditions averaging 10 kilometers an hour. Although the numbers will vary slightly depending on detonation depth, geology and weapon details, the basic results will be similar. If it takes six hours for people in the vicinity to evacuate, then calculations show that nearly everyone downwind of the blast within approximately five kilometers would still be killed by fallout, and half the inhabitants eight kilometers away would die. Only if the nearest population center is 10 or more kilometers downwind will the fallout lead to few if any rapid fatalities.

Even if the number of casualties were small, extensive areas adjacent to the blast zone would be contaminated with radioactivity. As an indicator of what level of exposure people might accept, after the Chernobyl disaster in Ukraine, authorities permanently closed off the region in which residents would be expected to receive a radiation dose of two rems in their first year (a rem is a unit of damage to tissue, averaged over the body, from ionizing radiation). By those standards, in the above scenario everyone downwind within 70 kilometers would need to relocate at least temporarily. Thirty kilometers downwind, people could return after a month; 15 kilometers downwind, they would have to wait a year to return home.

Fallout from a nuclear bunker buster could also complicate American military operations. Circumstances might force friendly troops to accept greater doses of radiation than civilians would, but these weapons could still render significant areas of a nearby battlefield off-limits. The U.S. Army recommends that troops willing to take "moderate" levels of risk be exposed to no more than 70 rems of radiation. Assuming that troops would be deployed to the area in 24-hour rotations, for the one-kiloton bomb example above, foot soldiers would have to stay at least 15 kilometers downwind of the blast until an hour after the attack and at least five kilometers downwind for a day or more. If the troops were forced to tolerate "emergency" exposure levels—up to 150 rems—those distances would be 10 and three kilometers, respectively [*see table on page 72*].

GROUND-PENETRATING WEAPONS TECHNOLOGY

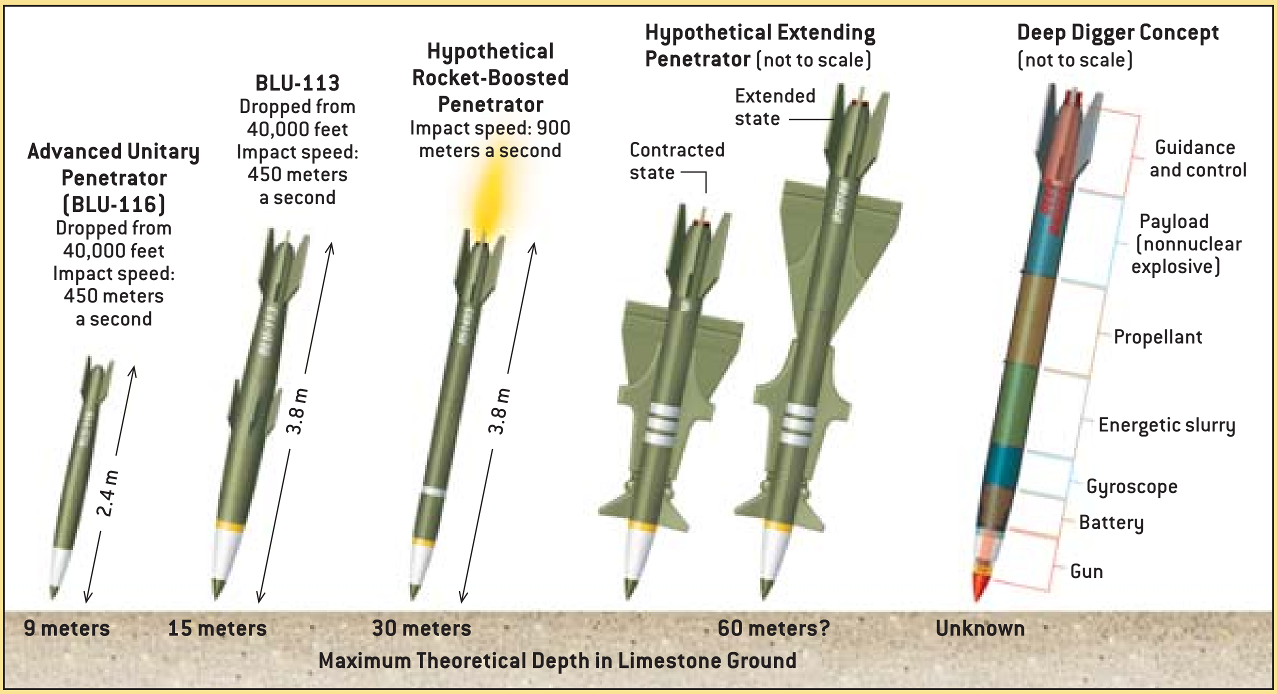
Several technologies under development could enable bombs to dive deeper and improve their accuracy in hitting an underground bunker. Most current earth-penetrating munitions achieve their high impact speeds—around 450 meters a second—simply from the force of gravity when dropped from far above. Adding rocket propulsion could double this velocity—and thus the impact momentum—which would drive bombs down to depths 75 percent deeper in hard granite and nearly 1,000 percent deeper in soft soil. Speeds greater than roughly 900 meters a second would cause a missile to disintegrate on contact with a hard-rock surface. In theory, doubling a missile's length (and thus, its mass) will double its penetration depth. In practice, however, a weapon's length is limited by the payload space available in the aircraft that delivers it.

To overcome fundamental limits in conventional kinetic earth-penetrating technologies, active devices could be built that drive into the ground. Deep Digger, a concept currently under development, is a good example. It would operate on principles similar to those used in "dry drilling" by the petroleum industry. In this process, a reciprocating metal head pulverizes the rock ahead, which is then cleared away by high-pressure gas. The Deep Digger concept would break up rock in its path with a rapid-fire gun.

Uncertainty over the depth of a buried target could be addressed with technology similar to the Pentagon's recently canceled Hard Target Smart Fuse, which carried an acceleration sensor to determine when a weapon had reached its goal. As the warhead passed from hard earth into the open bunker space, the accelerometer would register the change in resistance, prompting the fuse to detonate the payload. *—M.L.*


TEST OF THE HARD TARGET SMART FUSE

EARTH PENETRATORS



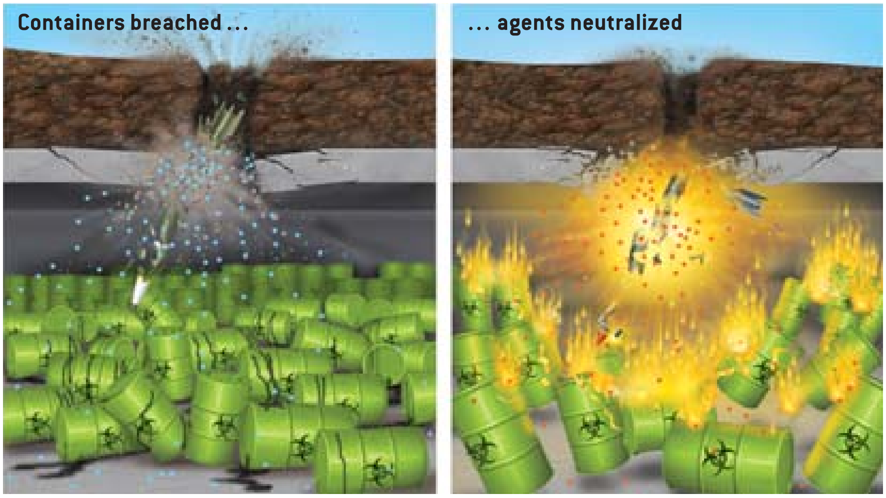
KENT SNODGRASS *Precision Graphics*; COURTESY OF AIR FORCE PHOTO

Nonnuclear Alternatives

THE COMPLICATIONS FROM atomic fallout naturally raise the question of whether any nonnuclear alternative could destroy deeply buried bunkers. Some technologies might be able to do the job, at least eventually. One of today's most effective bunker-busting weapons is the new Big-BLU bomb, which contains 15 tons of conventional explosives. But further advances in the power of nonnuclear explosives will be incremental and so are unlikely to deliver the sheer power of even a one-kiloton nuclear device.

To partially compensate for less destructive power, however, engineers can design earth-penetrating technology that allows a nonnuclear warhead to dive deeper and detonate closer to its target. Missiles that are simple kinetic penetrators ram through earth by dint of their extreme impact momentum. The greater that initial momentum (mass times speed), the longer the weapon takes to slow to a

AGENT-DEFEAT WEAPONS CONCEPT



MUNITIONS EXPERTS are developing technologies to render lethal chemical and biological agents inert before they can leak to the surface. These dedicated agent-defeat warheads generally employ a combination of separate mechanisms: fragmenting materials or clusters of small bombs to break chemical or biological agents out of their storage containers, followed by incendiary or chemical compounds to destroy or render the toxic substances safe.

stop after hitting the surface. The depth they reach can therefore best be extended by boosting the missile's velocity or its length (and thus, its mass), or both.

Most current earth-penetrating missiles achieve their impact speeds—around 450 meters a second—simply from the force of gravity. Adding rocket propulsion could double this velocity—and thus the impact momentum—which would drive them to depths 75 percent greater in granite formations and nearly 1,000 percent greater in soft soil. Most missile technologists consider speed increases significantly beyond that point to be infeasible because the missile would disintegrate on contact with the surface.

Under most impact conditions, doubling a missile's length (and hence, its momentum) will double its penetration depth. In practice, however, a missile's length is usually limited by the payload space available in the aircraft that delivers it. Fighter planes can carry only fairly short bombs; bombers are necessary to transport longer, more effective penetrators. To date, most burrowing munitions employed by the U.S. military are constrained by the policy requirement that they fit in a wide range of aircraft, including fighters. Relaxing this restriction would lead to the development of weapons that could burrow farther.

To overcome fundamental limits in traditional kinetic earth-penetrating technologies, active devices could be built. One example of this approach is called Deep Digger, a concept currently under development. Deep Digger would operate on principles that resemble "dry-drilling" techniques employed by the oil and gas industry. Dry drilling relies on a reciprocating metal head that pulverizes the rock in its path, which is then cleared from the borehole by high-pressure gas. The Deep Digger design is similar but much smaller; rather than weighing thousands of tons, it comes in at 50 to 100 kilograms. Such a device would be highly portable and could be delivered either by ground forces or by air. It could carry its own warhead or prepare the ground for delivery of a separate bomb. This particular technology may or may not ultimately work—but it demonstrates the potential of innovative solutions.

Because the radius of destruction around an exploding conventional warhead would be far smaller than that surrounding a nuclear weapon, the nonnuclear alternative could be less effective if the location of an underground bunker is only poorly known. For that reason, weapons designers are developing Small Diameter Bombs. These devices act much like underground cluster munitions, spreading multiple warheads over a wide area and thus mimicking the effect of a much larger explosive payload.

Uncertainty about the depth of a bunker can also be addressed to some degree by a technology similar to the Pentagon's recently canceled Hard Target Smart Fuse, which relied on an accelerometer to detect when a weapon has reached its goal. As the warhead passed from the hard earth into the bunker, the acceleration sensor would register the change in resistance and the fuse would detonate the payload on target.

To be sure, these enhanced penetration concepts could be applied to nuclear munitions as well. But if a bomb can be delivered close to its target bunker, the explosive power of a nuclear warhead may be superfluous; a conventional warhead will usually do.

Lights Out

SOME MIGHT STILL argue that earth-penetrating technologies are ultimately inadequate for conventional warheads to demolish hardened bunkers very deep underground. This is true, but there are bunkers—those below a few hundred meters—too deep to be annihilated by the biggest nuclear bombs. More important, destroying subsurface bases of operation is not always strategically necessary. U.S. forces may often want to leave a bunker intact, most likely to preserve it for analysis by military intelligence. In such cases, they will aim for functional defeat: rendering a target useless without actually wrecking it.

Sealing the entrances to a tunnel system is often the simplest way to disable it. Cruise missiles launched from afar or

THE AUTHOR

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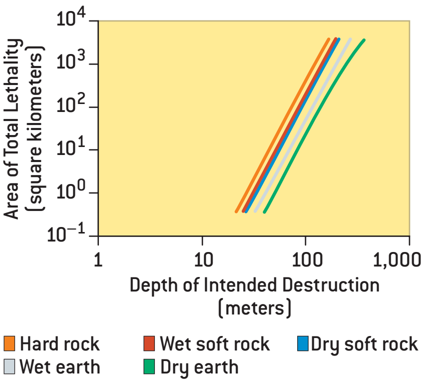
KENT SNODGRASS *Precision Graphics*

DISABLING buried, hardened bunkers might be accomplished without NUCLEAR BOMBS.

by charges placed by special forces can collapse tunnel entrances, trapping a facility's contents. Some commentators maintain that tunnel entrances will be hard to locate, but they will be far easier to find than the underground bunkers themselves.

Against headquarters facilities, the simple sealing approach will probably not succeed. Even if all the entrances are blocked, communications lines may survive, permitting the base to continue to function. To destroy or cripple power and communications lines leading into the target, U.S. forces may need to physically bomb or to employ the Pentagon's E-bomb, which emits a powerful microwave pulse. It is hard to imagine a scenario, however, in which a nuclear weapon would be of much greater value than a conventional bomb for merely taking a bunker out of service.

ESTIMATING LETHALITY



THE DEEPER THE ENEMY BUNKER a nuclear bomb is intended to reach, the greater the surface area affected by deadly doses of fallout—in geometric proportion. Soil composition is also a factor. This calculation assumes that nearby civilians can evacuate in three hours.

Risk Level 24 Hours after Attack

	Emergency risk	Chance of fatalities
1-kiloton bomb	3 kilometers	2 kilometers
1-megaton bomb	100 kilometers	55 kilometers

COMPLICATIONS FOR U.S. TROOP DEPLOYMENT would arise after the use of a nuclear bunker-busting weapon. If troops waited 24 hours before nearing the target zone and remained for a day, how far downwind from ground zero would they have to stay to be safe? The chart above indicates the distance to safe areas, depending on the bomb yield and on the radiological exposure tolerated by soldiers. For example, an individual willing to enter the zone an hour after an attack with a one-kiloton bomb who accepted "emergency" risk levels would have to stay at least 3 kilometers downwind.

Nuking the Village to Save It

ALL THESE NONNUCLEAR technologies suggest that the job of demolishing or disabling buried, hardened bunkers and weapons storehouses might be accomplished without nuclear bombs. Proponents of nuclear bunker busters counter with the following argument: atomic-tipped missiles used against underground weapons caches or laboratories can neutralize dangerous chemical and biological agents that a conventional explosive might just disperse. The result might be less collateral damage, they claim, because casualties from radioactive fallout would be offset by fewer deaths from leaking biological or chemical agents. This contention might turn out to be valid, but the case is not that simple.

Nuclear weapons would destroy chemical and biological materials by blasting them out of their containers and then rapidly heating them. Fairly modest temperatures of roughly 200 degrees Celsius applied for tens of milliseconds will neutralize most biological agents (powdered anthrax can take 50 degrees more), a temperature sustained easily by a nuclear weapon. If a nuclear bomb detonates in the same small bunker as a target bioagent cache, that storage facility will almost assuredly be eliminated. Whether a nuclear device that explodes outside a target bunker in the surrounding rock will neutralize all the biological agents it ejects as fallout remains a subject of active investigation and debate.

Eliminating chemical agents is much more difficult, in contrast, because the strong molecular bonds holding them together must be broken—a task that typically requires achieving temperatures upward of 1,000 degrees C for as long as a second. Although zones near the nuclear bomb—within meters for a kiloton-size warhead—will certainly reach this temperature, chemical munitions stored farther away will probably escape. Unfortunately, the nuclear blast is also apt to be sufficiently powerful to scatter those surviving agents.

Meanwhile various innovations might enhance the efficiency of conventional warheads in neutralizing dangerous substances. Military engineers are developing specialized agent-defeat technologies to render the lethal materials inert before they get a chance to leak into the surrounding region. These special warheads typically rely on a combination of separate mechanisms—fragmenting materials or clusters of small bombs to break agents out of their storage containers, followed by incendiary or chemical compounds to render the toxic substances safe.

Fuel-air explosives (which deliver a combination of extremely high heat and sustained pressure) and incendiary weapons can easily sustain the 200-degree temperatures needed to deactivate bioagents but will have difficulty maintaining the 1,000-degree temperatures needed to render many noxious chemicals inert. For that reason, payloads deployed against chemical weapons are more likely to rely on specialized reagents that react with the target to produce harmless by-products.

A Grave Decision

THE PRECEDING DISCUSSION delineates a few of the problems with using nuclear bunker busters and the range of practical alternatives. But not all questions concern the battlefield. One crucial question is whether new tactical nuclear weapons can be developed without resuming nuclear testing.

Nuclear tests would not be needed for some new arms technologies. Crude

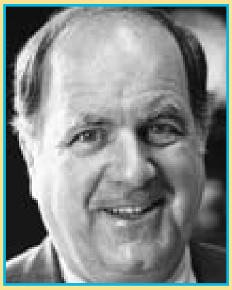
JOHNNY JOHNSON

DEBATING THE BAN ON SMALL NUCLEAR WEAPONS

For the past decade, one of the most significant impediments to the development of small nuclear weapons was not technological but legal. For the U.S. to pursue such devices, Congress first had to repeal a law that prohibited their development.

In 1993 Congress enacted a prohibition—called the Spratt-Furse ban—against any research that could lead to a new, small, nuclear weapon, one with a yield of less than five kilotons. Led by Representative John Spratt of South Carolina and then Representative Elizabeth Furse of Oregon, the legislature sought to continue the moratorium on nuclear testing begun by President George H. W. Bush. Some of the lawmakers also sought to forestall nascent efforts to build a new generation of small nuclear arms.

Despite several attempts to repeal the Spratt-Furse ban, it remained in force through early 2003. At that point, President George W. Bush asked Congress to overturn the law. Administration officials argued that low-explosive-yield nuclear weapons were among the most promising concepts for deterring rogue states because they lessened the danger to noncombatants; without the freedom to study such munitions, decision makers would never be able to explore the utility of the new technologies.



JOHN SPRATT

ELIZABETH FURSE

Strategic theorists who favored the ban's repeal also contended that potential adversaries might choose to ignore America's existing nuclear advantage. Why would any enemy believe that the U.S. would use its large nuclear munitions when the concomitant fallout would put so many civilians at risk? Enemies might instead decide that they could attack America with impunity. Less powerful nuclear weapons, however, might be more usable and thus more credible as a deterrent, the theorists argued.

Until 2003, a slim majority in Congress favored retaining the Spratt-Furse ban, however. They maintained that smaller nuclear bombs would be more destabilizing because officials would worry less about the collateral damage and so be more likely to use them. Downsized weapons would, in addition, blur the traditional firebreak between nuclear and nonnuclear arms, and that ambiguity would weaken international efforts to stop the spread of nuclear weapons technology. Thus, any use of nuclear weapons would make more widespread use of all types easier.

Some defenders of the ban argued that these substantially new weapons systems would require demonstrations to certify them. According to this line of reasoning, repeal of the Spratt-Furse prohibition would constitute the first step toward a resumption of nuclear testing, threatening international arms-control efforts.

In May 2003, in a near-party-line vote, the Spratt-Furse ban was repealed. Only months later, in December, National Nuclear Security Administration administrator Linton Brooks sent a memo to the nuclear weapons laboratories urging that they should "not fail to take advantage of this opportunity" to explore new nuclear designs. *—M.L.*

nuclear bunker busters, for example, could be designed on the basis of sophisticated computer models, old experimental data and nonnuclear field tests. To understand the massive deceleration a weapon would experience on impact, engineers could draw on experience with nuclear artillery shells fired from cannons. Still, military planners may be reluctant to fully trust a weapon that has never been field-tested.

Nuclear technologies for neutralizing chemical and biological agents would almost certainly need real-world evaluation. Designers would require sophisticated understanding of the interaction between a weapon's blast and heat and the targeted materials. Cold war–era munitions were designed to destroy bunkers, but none were expected to eliminate chemical and biological agents. The resulting paucity of experimental data would cripple development efforts. Presumably, only new tests would provide that information adequately.

Proponents have presented nuclear bunker busters as military necessities, whereas their opponents have insisted that these bombs have no utility at all. The reality is less clear-cut. Weighed against the best possible conventional arms, nuclear bunker busters do promise to afford some special advantages. But these are far fewer than their supporters typically suggest, particularly if creative conventional alternatives are explored. If American policymakers ultimately choose to develop these new nuclear bombs, they must do so not on the basis of wishful thinking, but with hardheaded reality in mind. SA

MORE TO EXPLORE

Countering the Threat of the Well-Armed Tyrant: A Modest Proposal for Small Nuclear Weapons. Thomas Dowler and Joseph Howard II in *Strategic Review,* Vol. 19, pages 34–40; Fall 1991.

Low-Yield Earth-Penetrating Nuclear Weapons. Robert W. Nelson in *Science and Global Security,* Vol. 10, No. 1, pages 1–20; January 2002.

Fire in the Hole: Nuclear and Non-Nuclear Options for Counterproliferation. Michael Levi. Working paper No. 31, 2002, Carnegie Endowment for International Peace. Available at **www.ceip.org/files/pdf/wp31.pdf**

Effectiveness of Nuclear Weapons against Buried Biological Agents. Michael May and Zachary Haldeman. Report from the Stanford Center for International Security and Cooperation, June 2003. Available at **http://iis-db.stanford.edu/pubs/20216/MayHaldeman0104.pdf**

An Analysis of Reduced Collateral Damage Nuclear Weapons. Bryan L. Fearey, Paul C. White, John St. Ledger and John D. Immele in *Comparative Strategy,* Vol. 22, No. 4, pages 305–324; October/November 2003.

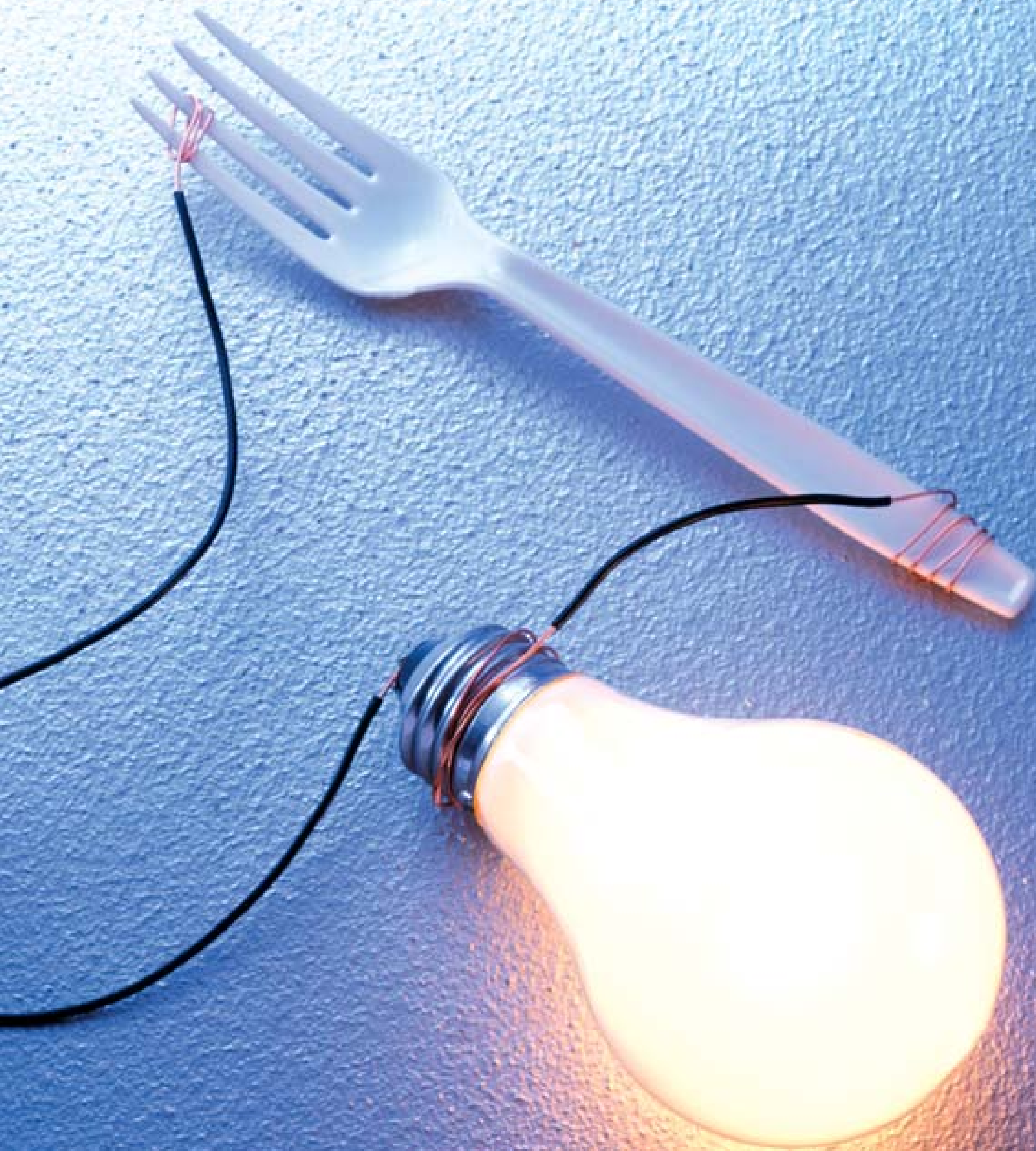
COURTESY OF THE OFFICE OF JOHN SPRATT (*top*); COURTESY OF ELIZABETH FURSE (*bottom*)

Next Stretch for PLASTIC

Organic semiconductor devices can make more than just bendable displays. They will find use in wearable electronics, chemical sensors, skin for robots and innumerable other applications

ELECTRONICS

By Graham P. Collins



Strong, flexible, lightweight and cheap, plastics have acquired an additional attribute in recent years: the ability to function as semiconductors, forming diodes and transistors in plastic integrated circuits. Now, as the first plastic electronics products are hitting the market in displays that use organic light-emitting diodes, the stage is set for a new era of pervasive computing with polymers. Plastics may never match the sheer processing speed and miniaturization of silicon, but they will be able to go places that silicon cannot reach: ultracheap radio-frequency identification tags; low-end, high-volume data storage; displays that are inexpensive, even disposable, or that can be wrapped around a wall column; and wearable computing. Other uses for conductive plastics include photocells, chemical sensors and pressure-sensitive materials.

A key advantage of organic transistors over silicon is their ease of fabrication. Building a state-of-the-art silicon chip takes weeks of work using complex and expensive processes such as photolithography and vacuum deposition, carried out under high temperatures in ultraclean rooms. In comparison, organic transistors can be made using faster, cheaper processes under less carefully controlled conditions. Finally, there is the promise of "roll-to-roll" fabrication similar to the continuous printing presses that revolutionized publishing.

Overview/*Plastic Electronics*

- Plastics have long formed the skeletons and skin of products, whereas silicon has supplied the brains. With the advent of polymer and crystalline organic electronics, plastics will make up the brains as well as the brawn.
- Plastic chips may never be as fast or as miniaturized as silicon chips, but their production by convenient techniques, including ink-jet printing, promises extremely cheap devices that could become ubiquitous in consumer products and household appliances.
- Potential uses include information displays for appliances and computers, electronic paper, radio-frequency identification tags, wearable electronics, chemical sensors and pressure-sensitive skin for robots.

Organic Semiconductors

THE CONDUCTIVE PLASTICS in electronics come in two broad types. One is made out of small organic molecules, the other out of long, conjugated polymer molecules. An example of the small-molecule variant is pentacene, which consists of five benzene rings joined in a line [*see box on page 78*]. The long polymers consist of chains of hundreds or thousands of carbon atoms. "Conjugated" means that the carbon atoms in the chains are joined by alternating double and single bonds. A benzene ring can also be thought of as a short chain of six such carbon atoms, with alternating bonds, biting its tail to form a closed loop. But that picture of alternating single and double bonds is not the most accurate way of viewing any of these molecules. Instead some of the double-bond electrons become delocalized, shared among several atoms rather than localized in a specific bond between two atoms.

Such delocalization is similar to what happens in metals and semiconductors. The delocalized electrons can exist only in states that have specific energy levels. The permitted energies form bands that can hold only so many electrons [*see box on page 78*]. The highest-energy band containing electrons is called the valence band, and the next higher one is the conduction band.

The small molecules, such as pentacene, are conductive in their pure state, and they can be made directly into crystals or thin films for use in devices. The long polymers, in contrast, are generally poor conductors in their pure state. The reason is that their valence band is full of electrons, which obstructs current flow. Each electron in the band has nowhere to go—it has no

LEONARD GERTZ (*preceding pages*)

empty states available where it can move. The empty spaces in the conduction band are at too high an energy level to be of use.

To change that situation, researchers introduce special impurity atoms (called doping). The dopant atoms either add extra electrons, which go into the conduction band, or they remove some electrons from the valence band, creating holes, which behave like positive particles. In either case, current can flow easily, either by conduction electrons traveling along in the almost empty conduction band or by holes traveling through the valence band. (From the perspective of a hole, the valence band is almost empty: every electron there is akin to a location to which the hole can move.)

The possibility of doping conjugated polymers in this way to create a conducting or semiconducting material was discovered in the 1970s by Alan J. Heeger (now at the University of California at Santa Barbara), Alan G. MacDiarmid (now at the University of Pennsylvania), Hideki Shirakawa (now at the University of Tsukuba in Japan) and their co-workers. Heeger, MacDiarmid and Shirakawa received the 2000 Nobel Prize in Chemistry for this work. They doped polyacetylene by exposing it in various experiments to chlorine, bromine or iodine.

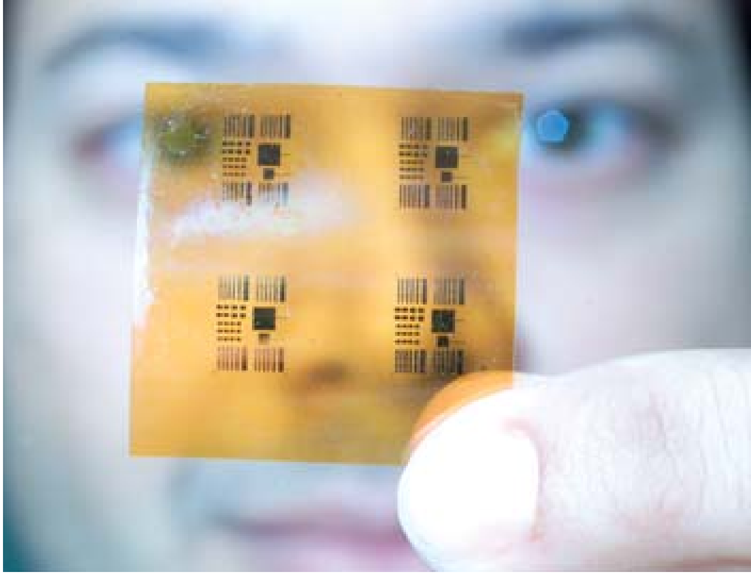
These conductive plastics have already found a number of applications other than electronic circuitry, including use as a corrosion inhibitor, electromagnetic shielding for electronic circuits, an antistatic coating on photographic emulsions, and a microwave-absorbing stealth coating to hide an object from radar.

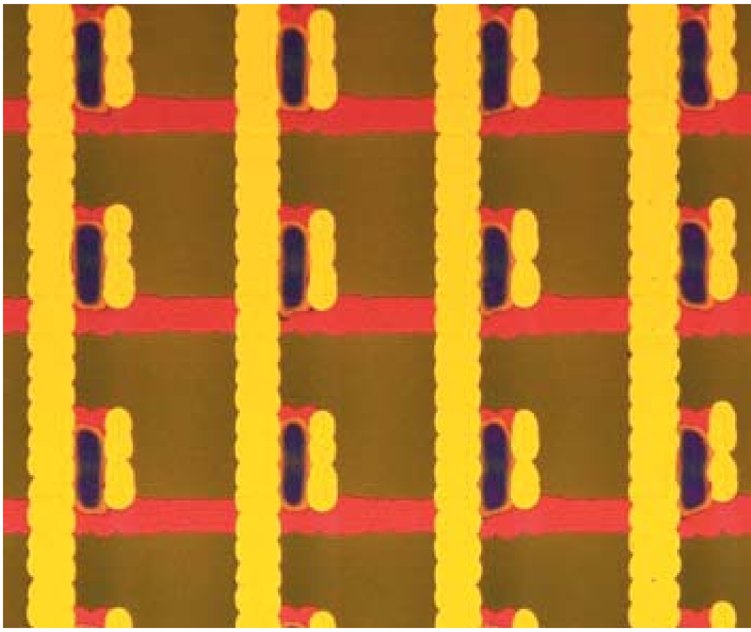
Printing Machines

THE SMALL-MOLECULE organic semiconductors are best fabricated into devices by vapor deposition: the compound is vaporized in a closed chamber, either evacuated or filled with an inert gas, and allowed to condense in a film onto a substrate. This technique is similar to that used in the manufacture of some very quotidian products, such as the coating on potato chip bags that prevents oxygen from diffusing through the plastic.

Polymers offer a number of fabrication techniques. One is spin-coating, in which a disk with a blob of a solution containing the polymer or its precursors is spun, spreading the material evenly across the disk. The material can then be etched by photolithographic techniques similar to those used in making conventional inorganic semiconductors or cut or imprinted in other ways. (Some researchers have also used spin-coating with pentacene.)

One problem with conductive polymers compared with the plastics used in other industries is their lack of solubility in convenient organic solvents. For example, polyethylenedioxythiophene, or PEDOT, is typically laid down in an acidic water-based solution whose corrosive properties cause other problems. In April, TDA Research in Wheat Ridge, Colo., announced a new form of PEDOT dubbed oligotron, which is soluble in noncorrosive organic solvents. Shining ultraviolet (UV) light on the liquid precursor causes its molecules to cross-link, curing the material into an insoluble solid. Thus, it should be possible to spin-coat oligotron and then make a pattern by shining UV light on it through a mask.





PLASTIC TRANSISTOR ARRAYS were patterned using ink-jet printing by the Palo Alto Research Center (PARC). The lower image shows 12 transistors of an array. The dots are about 40 microns in diameter. The researchers used a semiconducting polymer ink developed by Beng Ong of the Xerox Research Center of Canada. The transistors would be suitable for use in active-matrix displays, electronic paper and other applications.

PARC (*top*); ANA ARIAS *PARC* (*bottom*)

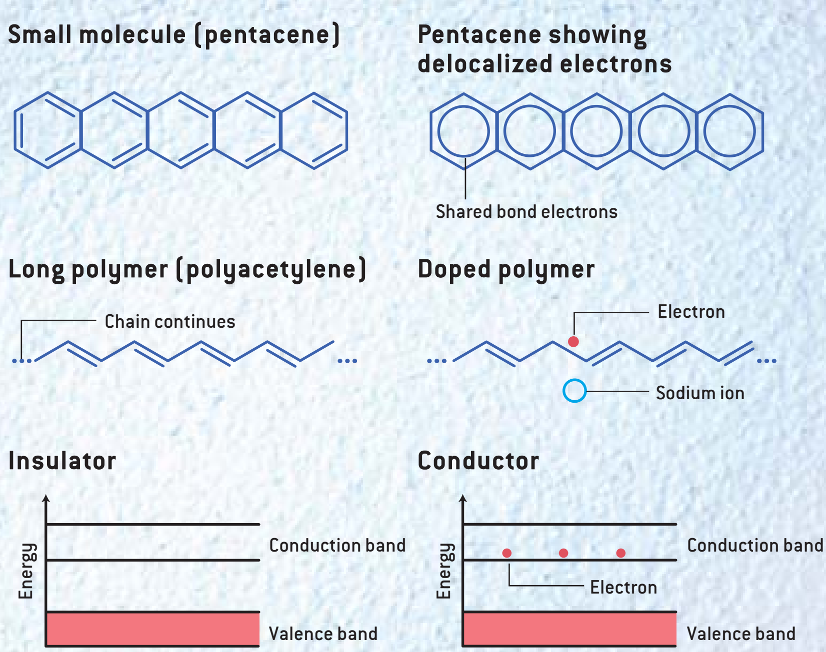
Alternatively, it could be ink-jet-printed in a pattern and then fixed with UV radiation. The ink-jet process is highly analogous to graphical ink-jet printing, but instead of colored dyes, tiny droplets of polymer solution are propelled onto the substrate in carefully controlled patterns. So far only a large-scale proof-of-principle pattern has been demonstrated; no electronic devices have been made.

The trick to making oligotron soluble was to attach appropriate groups on the end of the PEDOT monomer molecules. It should be possible to create variants of oligotron with specific properties by modifying the end groups. For instance, oligotron with photovoltaic end groups might be used to make solar cells.

Several companies are pursuing the ink-jet technique of circuitry printing. The Palo Alto Research Center (PARC, formerly a part of Xerox) has demonstrated such technology; in 2003 its researchers produced the first plastic semiconductor transis-

CONDUCTIVE PLASTICS

The raw materials for organic electronic devices come in two broad classes: small molecules (*top*) and conjugated polymer chains (*middle*), both of which have alternating double and single carbon bonds. (Each line in these diagrams is a bond between two carbon atoms. Bonds to hydrogen atoms are not shown.) Electrons in the double bonds become somewhat delocalized, or shared among many atoms. Consequently, the allowed states of the electrons form bands over ranges of energy (*bottom*). The electrical properties of the material depend on the separation and the filling of the bands. Generally, the polymers have a full valence band, making them insulating. When dopant chemicals (such as sodium) are added, however, electrons contributed to the conduction band or removed from the valence band enable a current to flow. The small molecules are semiconducting in their undoped state.



LUCY READING

tor array built entirely by ink-jet printing [*see illustration on preceding page*]. The transistors are larger than their silicon cousins and switch more slowly, but their mobility—0.1 square centimeter per volt per second (cm^2/Vs)—is only a factor of 10 lower than that of amorphous silicon, which is widely used in the backplanes of liquid-crystal computer displays. (Mobility is a measure of how readily charge carriers such as electrons travel in a material. A factor of 10 is a relatively small difference; amorphous silicon lags behind crystalline silicon by a factor of 1,000.)

Dow, Motorola and Xerox have formed an alliance to develop polymer inks and printing methods, as have DuPont and Lucent Technologies, as well as Universal Display Corporation and Sarnoff.

At the 2003 Society for Information Display Conference, Plastic Logic demonstrated what it claimed to be the first plastic-electronics ink-jet-printed active-matrix display. (In active-matrix displays, each pixel is powered by its own transistor.) The display, which had a 63-by-48 array of pixels on a glass backplane about two and a half centimeters square, used the electronic paper of Xerox spin-off Gyricon. Plastic Logic and Gyricon are working to increase the display size, improve resolution and move to a flexible plastic substrate.

Thus far the ink-jet-printing process cannot produce transistors as small and as tightly packed together as in the best inorganic chips. But in mid-2003 researchers at Cornell University, using electron-beam lithography on pentacene, demonstrated that properly functioning organic thin-film transistors could be constructed with a channel length as small as 30 nanometers, comparable to the channel lengths in today's silicon transistors. (The channel is where an electric current flows through a transistor—or not—and where the switching action takes place.) Previous attempts at making ultrasmall organic thin-film transistors had been successful only down to 100 nanometers; smaller devices had exhibited impaired performance. Electron-beam lithography is an expensive process and would not be the method of choice to produce organic devices commercially, but the Cornell work demonstrates that such small devices are possible.

Organics have other shortcomings in addition to size. One drawback is the lack of a suitable material for making *p*-type and *n*-type transistors together on a single chip, a prerequisite for what is called complementary metal oxide–semiconductor (CMOS) technology, which is the mainstay of microprocessors. (In *p*-type semiconductors the current carriers are holes; in *n*-type, electrons.)

In addition, many polymer materials are fragile, susceptible to damage by humidity or mere exposure to oxygen in the air. This weakness can be addressed by sealing the active components inside airtight and moisture-tight layers, but that solution adds further steps to fabrication and impairs desired properties such as thinness and flexibility.

Some progress has been made in developing sturdier materials. In April, Beng Ong of the Xerox Research Center of Canada announced the development of a polythiophene ink that is not sensitive to oxygen; it can be used to print circuitry without needing a special inert atmosphere.

A sturdy organic-inorganic hybrid was developed by David Bocian of the University of California at Riverside. In November 2003 his team reported that organic molecules called porphyrins, which are made of strings and rings of carbon atoms, could be bonded to the oxidized surface of a silicon substrate. The por-

Organic semiconductors' slower switching speeds are more than adequate for driving displays.

phyrins could withstand up to 400 degrees Celsius for 30 minutes.

One way to avoid damaging the fragile organic part of a device during fabrication is to separate the production of the organic part from the patterning of the other circuitry involved. This method was reported in March by John Rogers of the University of Illinois and his co-workers from Lucent and Rutgers University. They used vapor deposition to lay down thin gold electrodes onto a flexible rubber substrate. This stamp was pressed against a large, high-quality crystal of rubrene to form a transistor. (Rubrene is four benzene rings in a chain with four more attached individually as side groups like two pairs of wings.) The technique avoids exposing the organic crystal to the harsh conditions of the electrode deposition and thereby prevents damage.

The group recorded the highest mobility rates ever seen in an organic transistor—up to 15 cm^2/Vs. The stamp process might have commercial applications, but it was developed for research purposes. The scientists could remove and reposition the stamp repeatedly. By changing its orientation, they determined that the mobility depended on the direction of travel through the crystal, an effect long expected in the organics field but never before so clearly demonstrated.

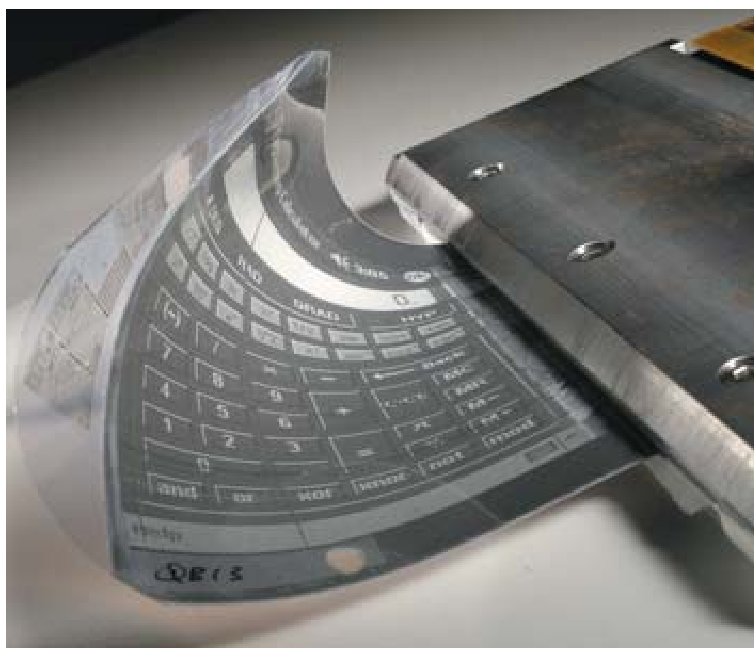
Displays and RFIDs

IN GENERAL, organic semiconductors have lower mobility than their inorganic counterparts do, resulting in slower switching speeds. Clock frequencies up to hundreds of kilohertz might be achievable, but don't look for gigahertz-rated organic chips anytime soon. Those speeds, however, are more than adequate for driving displays.

Products containing the first rudimentary displays using conductive plastics are now selling, including a Kodak digital camera with a five-centimeter plastic-electronics view screen and a Philips electric shaver that shows battery charge. Both organic (small-molecule) and polymer (large-molecule) light-emitting diodes can serve as the pixels of a display in a way that is impractical with LEDs made of silicon. The transistors that control each pixel can also be made of plastic semiconductors [see "Better Displays with Organic Films," by Webster E. Howard; SCIENTIFIC AMERICAN, February].

Another display application is electronic paper, in which the display is reflective instead of emissive, made up of tiny beads or microcapsules that change between white and black states [see "The Electronic Paper Chase," by Steve Ditlea; SCIENTIFIC AMERICAN, November 2001]. Rigid versions of electronic paper are already in use as programmable displays in department stores. In January, Polymer Vision, a division of Royal Philips Electronics in the Netherlands, released a prototype that combines the e-paper developed by Massachusetts-based E Ink with a flexible, paper-thin backplane of 80,000 organic transistors. The device is a rectangular screen measuring 12.5 centimeters diagonally. Merely three times the thickness of paper, it can be rolled into a four-centimeter-diameter tube [*see illustration below*]. The circuitry of the device is entirely plastic, except for some ultrathin gold wiring. This is the first flexible display to be mass-produced; 100 are rolling off Polymer Vision's pilot production line every week.

Plastic electronics will also soon be coming to market in radio-frequency identification tags (RFIDs). Metal and silicon-based RFIDs are already in use in automatic toll-payment systems. When a car passes through an RFID-equipped toll plaza, a reader sends out a radio signal that activates the RFID chip in a card on the car's windshield. The card responds with a code that identifies the car, and the toll is deducted from the corre-



ELECTRONIC PAPER produced by Philips has a resolution of 85 pixels per inch and can be rolled up into a cylinder four centimeters in diameter. The paper uses pentacene thin-film transistors that are manufactured at room temperature from a liquid solution. The transistors operate fast enough to display video.

ROYAL PHILIPS ELECTRONICS

PRESSURE-SENSITIVE "SKIN" could give robots a sense of touch. Developed by Takao Someya and his co-workers at the University of Tokyo, each sensor is about three millimeters square. Individual square patches of sensors can be linked up to cover larger areas simply by taping them together with their electrodes aligned. The transistors controlling the sensors are made of pentacene.

TAKAO SOMEYA *University of Tokyo*

sponding account. At present, the cost of such silicon-based RFID tags is around $0.25, which is low enough for something like a toll-payment system but far too expensive for other proposed uses, such as the tagging of every item in a supermarket to facilitate stock tracking and customer checkout. Plastic RFID chips could bring the cost down to a penny or less, making their ubiquitous use in place of bar codes more viable. [See "RFID: A Key to Automating Everything," by Roy Want; SCIENTIFIC AMERICAN, January; and "Penny-wise Smart Labels," by Steven Ashley; Innovations, on page 30.]

Memory, Noses and Skin

BEYOND LEDS for displays and RFID chips, organic circuitry has many other potential applications. For example, in December 2003 at the annual International Electron Devices Meeting (IEDM), researchers from Infineon described two different types of memory chip based on organic polymers. One was a form of nonvolatile memory, meaning one that retains its data when the power is turned off. Infineon investigators demonstrated that their chips could retain data for more than a year and claimed that the material could potentially be patterned with features as small as 20 nanometers.

The second was a type of dynamic random-access memory, or DRAM, in which each data bit consists of a transistor and a capacitor. Feature sizes were about 140 nanometers. The DRAM was made by a modified form of spin-coating, using a new polymer that is stable even above 450 degrees C, much higher than most conductive polymers can withstand.

Conducting plastics could also be at home in a very different type of device: the chemical sensor. Traditional versions of these have perhaps a dozen electrodes coated with polymer composites, such as polymers mixed with carbon black. Each electrode has a different type of polymer, and when these compounds are exposed to a specific gas, each one responds idiosyncratically—absorbing more or less of the gas in question. This occurrence in turn swells the polymer and alters the conductivity caused by the carbon particles. The pattern of conductance variations across the dozen polymers provides a signature for that specific gas.

Similar effects can be achieved using conducting or semiconducting polymers instead of the carbon-black composites. These conductive polymer sensors can operate straightforwardly by the change in electrical resistance of the polymer, but they can also be fashioned into capacitors or field-effect transistors whose characteristics change according to which gas has been absorbed into the polymer. Sensors made with conductive plastics could have greater sensitivity than the old composite

One can imagine electronic textiles with controllable properties, such as color for camouflage or information display.

versions; the transistors in particular could function as built-in amplifiers of the polymer response. A component's response to gases could depend on the detailed structure of the transistor as well as the type of polymer used. In 2001 Ananth Dodabalapur, now at the University of Texas at Austin, and his co-workers demonstrated such sensors using thin-film organic transistors. None are yet on the market. More recently, Dodabalapur has been studying nanoscopic chemical sensors. He has found that transistor-based sensors with channels as small as about 10 nanometers respond in a distinctly better fashion than larger sensors do.

Such sensors could be incorporated into the fabric of a person's clothing for wearable electronics. As reported at the 2003 IEDM conference, Vivek Subramanian and his colleagues from the University of California at Berkeley have demonstrated how to build transistors directly onto fibers. (His group has also worked on chemical sensors.) The transistors were actually made of a mixture of materials, including aluminum threads and gold contacts. The channels of the transistors were made of flexible pentacene with a mobility of 0.05 cm^2/Vs. Transistors were formed at every intersection of the crossed fibers. The entire fabrication was additive: laying down fibers and depositing other layers on them. By avoiding the need to etch away patterns, as occurs in conventional lithography, the process remains practical for scaling up to large areas of material.

Even though the transistor gates used an inflexible oxide as an insulating layer, the textile could be curved to the equivalent of a 15-centimeter cylinder without greatly impairing the transistor characteristics. Replacing the oxide with a flexible organic insulator should allow even tighter curvature.

One can imagine fabrics made of electronic textiles with controllable properties, including color for camouflage or information display, porosity to control sweating, and other changes to effect heating or cooling. Such wearable computers could also monitor the individual's vital signs or the surrounding environment. The network of threads would allow ripped or damaged fabrics to route signals around the broken region.

Much work remains to realize those goals. To begin with, the transistors need to be more durable to withstand bending and flexing of the material. Such applications do not, however, require high performance of the transistors.

If computerized clothing doesn't interest you, how about electronic skin? In November 2003 Takao Someya and his co-workers at the University of Tokyo announced the use of pentacene transistors in a flexible sheet to form a pressure-sensitive skin that could be used to give a robot a sense of touch [*see illustrations on opposite page*]. The pressure-sensitive part of the structure is a layer of carbon-rubber composite with a resistance that varies depending on how much it is compressed. That resistance change switches on an underlying transistor. The team produced units, each consisting of an array of 16-by-16 sensors, each sensor about three millimeters square, along with transistors for extracting the signals from the rows and columns.

To cover a larger area, units can be connected just by overlapping the electrodes at their edges and applying adhesive tape, but there is no reason why larger sensor units could not be made. The entire structure is made completely out of polymers and pentacene with the exception of gold electrodes and a copper coating that lies next to the carbon-rubber composite layer. The units can be bent down to a five-millimeter radius, good enough for encircling slender fingers. A shortcoming of the present design is the poor stability of the sensors' transistors—after only a couple of days their response degraded. Ideally, the sensors should last for months or years. Another problem is a high operating voltage—40 volts—which the researchers hope to lower to 10 volts.

Robots are not yet commonplace outside of industry, hobbies and toys (such as Sony's robot dog, Aibo). The U.N. Economic Commission for Europe estimates that only 50,000 domestic robots (mostly lawnmowers and vacuum cleaners) had been sold worldwide by the end of 2002, but they predict the number will grow by more than a factor of 10 by the end of 2006. Along with robots, smart appliances and products bristling with displays and sensors will increasingly pervade everyday life. Organic electronics will play a crucial role as this responsive, interactive future comes to fruition. SA

Graham P. Collins is a staff writer and editor.

MORE TO EXPLORE

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QUESTIONS That PLAGUE PHYSICS

Lawrence M. Krauss speaks about unfinished business

Chair of the physics department at Case Western Reserve University, Lawrence M. Krauss is famed in the research community for his prescient suggestion that a still mysterious entity called dark energy might be the key to understanding the beginnings of the universe. He is also an outspoken social critic and in February was among 60 prominent scientists who signed a letter entitled "Restoring Scientific Integrity in Policymaking," complaining of the Bush administration's misuse of science. The public, though, might know him best as an op-ed writer and author of books with mass appeal. His 1995 work, *The Physics of Star Trek,* became a best-seller, translated into 15 languages. He is now finishing his seventh popular title, *Hiding in the Mirror: The Mysterious Allure of Extra Dimensions,* which he describes as "an exploration of our long-standing literary, artistic and scientific love affair with the idea that there are hidden universes out there." Krauss recently discussed his many scientific and social passions with writer Claudia Dreifus.

SCIENTIFIC AMERICAN: What are the top questions bedeviling physicists today?

LAWRENCE KRAUSS: Three that I find fascinating are: What is the nature of dark energy? How can we reconcile black hole evaporation with quantum mechanics? And, finally, do extra dimensions exist? They are all connected. And they are all going to require some new insights into quantum gravity. But someone is going to have to come up with a totally new and remarkable idea. And it's hard to predict when that is going to happen. In 1904 you couldn't have predicted that Albert Einstein would come up with a remarkable idea in 1905.

I think the resolution to these problems is likely to be theoretical and not experimental. This is because direct experimental signatures that might point us in the right theoretical directions in these areas probably lie beyond the realm of current experiments. I'd also bet that the solution to these problems is not going to resemble anything being done now, including string theory.

SA: Is string theory the physics equivalent of The God That Failed, as some people used to say about communist ideology?

LK: Not exactly. But I do think its time may be past. String theory and the other modish physical theory, loop quantum gravity, both stem from one basic idea: that there's a mathematical problem with general relativity.

The idea is that when you try to examine physical phenomena on ever smaller scales, gravity acts worse and worse. Eventually, you get infinities. And almost all research to find a quantum theory of gravity is trying to understand these infinities. What string theory and what loop quantum gravity do is go around this by not going smaller than a certain distance scale, because if you do, things will behave differently. Both these theories are based on the idea that you can't go down to zero in a point particle, and that's one way to get rid of mathematical infinities. The main difference, I think, between the two theories is that string is intellectually and mathematically far richer.

String theory hasn't accomplished a lot in terms of solving physical problems, but it's produced a lot of interesting mathematical discoveries. That's why it fascinates. Loop quantum gravity hasn't even done that, at least in my mind.

SA: Are you saying that string theory hasn't really gotten us anywhere?

LK: Neither string theory nor loop quantum gravity has told us much about the key unsolved physical problems—most important, why does the universe have dark energy? That's the biggest question right now. One thing that has come out of string theory is the idea of plural universes or extra dimensions, and that's because string theory is based on extra dimensions. The only consistent string theory originally had 26 dimensions, and then it got lowered to 10. But the universe we live in is four-dimensional [three spatial plus time]. A lot of talk went into explaining how all these extra dimensions were invisible. Recently some people have been trying to turn that defect into a virtue by suggesting that the extra dimensions might actually be detectable.

SA: You've just finished writing a book about parallel universes. Do you think they're real?

LK: Let me answer you this way: it's an exciting area, and it's wonderful for graduate students. One of my former Ph.D. students is largely responsible for the recent surge of interest in this idea. But I think these extra dimensions smell wrong. What we are learning from elementary particle physics about the unification of all the forces in nature tends to point in a direction that is not the direction these large parallel universe models suggest. As beautiful and as sexy as they are, if I had to bet, I'd bet that these large extradimensional ideas are probably not right. We'll see.

SA: How did you come to write *The Physics of Star Trek?*

LK: Actually, it began as a joke, probably sometime in 1993. I had just finished *Fear of Physics* for Basic Books. I was chatting with my editor about what I might do for them next. Somewhere in the conversation, she mentioned something about her daughter's being a Trekker. "How about *The Physics of Star Trek?*" she laughed.

That night I started thinking about the transporter, a *Star Trek* device that disassembled your atoms, moved them almost instantaneously to somewhere else and reassembled them in that place. What might it take to build one? That led to my making a list of all these neat *Star Trek* phenomena that one could use to hook people into thinking about physics. If people loved this imaginary stuff, I thought, why couldn't they love real science, which is a thousand times more amazing?

I was blunt about *Trek* things that wouldn't work. But I also pointed readers toward more fascinating possibilities in the real universe. Real science comes up with ideas that no fiction writer would have the temerity to suggest. Think about cosmic antigravity, something I work on at my day job: no one understands why empty space should have energy. It's the weirdest idea in the world!

SA: Why?

LK: If you asked a child how much energy there is in empty space, he'd say "none," because that's the sensible answer. But what we've learned is that's not true: if you take everything away, there's still something there.

What's worse is: if you put a little amount of energy into empty space, then everything we know about the laws of physics says you should be able to put a tremendous amount of energy into it. Once you open the dam and allow empty space to have energy, you ask how much it should naturally have. Our current understanding of gravity and quantum mechanics says that empty space should have about 120 orders of magnitude more energy than the amount we measure it to have. That is 1 with 120 zeroes after it! How to reduce the amount it has by such a huge magnitude, without making it precisely zero, is a complete mystery. Among physicists, this is considered the worst fine-tuning problem in physics.

When we solve this problem, we're going to have to explain why the number that we measure is 120 orders of magnitude smaller than we would expect it to be. No

MARK JENKINSON

LAWRENCE M. KRAUSS is a man of many opinions. One is that string theory has failed to shed light on the nature of dark energy.

one has an idea how to do that. And that's why it's the most exciting thing in physics. Because weird makes things exciting.

SA: You are one of the few top physicists who is also known as a public intellectual. In the middle of the past century, that kind of activity by scientists was much more common. Albert Einstein, in fact, was an international celebrity, whose private views of everything from nuclear disarmament to Zionism were solicited by the press. Why do you think you're such a rare bird that way now?

"I'm not against teaching faith-based ideas in religious classes; I'm just against teaching them as if they were science."

LK: I can't speak for others. Besides my own research, I see part of my mission as trying to close the disconnect between science and the rest of the culture. We live in a society where it's considered okay for intelligent people to be scientifically illiterate. Now, it wasn't always that way. At the beginning of the 20th century, you could not be considered an intellectual unless you could discuss the key scientific issues of the day. Today you can pick up an important intellectual magazine and find a write-up of a science book with a reviewer unashamedly saying, "This was fascinating. I didn't understand it." If they were reviewing a work by John Kenneth Galbraith, they wouldn't flaunt their ignorance of economics.

SA: How did science illiteracy become socially acceptable?

LK: We all know how badly science is taught in many schools. So many middle school and even some high school teachers have no background in science. When my daughter was in the second grade and I went to her school, I was stunned by how her teacher seemed incredibly uncomfortable with having to teach even the simplest scientific concepts. I think this is common. And there is the reality that science has grown increasingly esoteric, making it more difficult for laypeople to grasp.

The truth is—and I'm hardly the first to say this—after World War II, American scientists became an isolated elite. The secrets that allowed them to change the world also allowed them to shirk responsibility for citizenship. Scientists became a class above society, rather than a part of it.

And so for the longest time, certainly until the 1970s, many American scientists just didn't believe that reaching the public was important. Those were good times, with lots of money coming in. The wake-up call came in 1993, when Congress killed the Superconducting Super Collider. That was a real signal physicists were doing something wrong.

We hadn't convinced the public—or even all of our colleagues—that it was worth billions to build this thing. And since then, it has become clear: to get money for what we do, we're going to have to explain it to the public. *My* predilection is to try to connect the interesting ideas in science to the rest of people's lives.

SA: The big public issue you've been identified with is fighting against creationist teachings in the schools. For the past couple years, you've spent your time traveling, debating creationists on proposed curriculum changes for Ohio's high schools. Was that fun?

KRAUSS (*standing*) spoke to the Ohio State Board of Education Standards Committee on March 11, 2002, in an effort to keep religious teachings out of the public school science curriculum. The board agreed, although creationists have not given up the fight.

JAY LAPRETE *AP Photo*

LK: It was the least fun of anything I've ever done. Convincing people of the excitement of science is fun; trying to stave off attacks on science feels like the most incredible waste of time, even if necessary.

I got drafted after several creationists were appointed to the Standards Committee of the Ohio State Board of Education. They were proposing new standards to create false controversy around evolution by introducing an ad hoc idea called intelligent design into high school science classes.

For nearly a year, I found myself in the middle of what was almost the equivalent of a political campaign.

When it was over, we won and we lost. We won because we had kept intelligent design out of science classes. We lost because in the spirit of "fairness," the board added a sentence to the standards saying, "Students should learn how scientists are continuing to critically examine evolutionary theory." I strongly opposed this. I wanted them to say that scientists are continuing to critically examine everything.

As I feared, this sentence opened the door for the creationists' claiming that there is controversy about the accuracy of evolutionary theory. And it's come back to haunt us. Just the other week, I had to put everything I was doing aside because the creationists were back at their old games again in Ohio. One of the model lessons that came out was an intelligent-design diatribe. Basically, they snuck the whole thing in again, through the back door. This becomes so tiresome that you just want to say, "Forget about it, go on." But then you realize that this is exactly what Phillip Johnson, this lawyer who first proposed the intelligent-design strategy, proposed when he said something like, "We'll just keep going and going and going till we outlast the evolutionists."

SA: Do scientists trap themselves when they try to be "fair" and "give equal time" in their debates with the anti-Darwinists?

LK: Yes. Because science isn't fair. It's testable. In science, we prove things by empirical methods, and we toss out things that have been disproved as wrong. Period. This is how we make progress.

I'm not against teaching faith-based ideas in religion classes; I'm just against teaching them as if they were science. And it disturbs me when someone like Bill Gates, whose philanthropy I otherwise admire, helps finance one of the major promoters of intelligent design by giving money to a largely conservative think tank called the Discovery Institute. Yes, they got a recent grant from the Gates Foundation. It's true that the almost $10-million grant, which is the second they received from Gates, doesn't support intelligent design, but it does add credibility to a group whose goals and activities are, based on my experiences with them, intellectually suspect. During the science standards debate in Ohio, institute operatives constantly tried to suggest that there was controversy about evolution where there wasn't and framed the debate in terms of a fairness issue, which it isn't. [*Editors' note: Amy Low, a media relations officer representing the Bill and Melinda Gates Foundation, says that the foundation "has decided not to respond to Dr. Krauss's comments."*]

SA: Why do you find this grant so particularly disturbing that you single it out here?

LK: Because we're living in a time when so many scientific questions are transformed into public relations campaigns—with truth going out the window in favor of sound bites and manufactured controversies. This is dangerous to science and society, because what we learn from observation and testing can't be subject to negotiation or spin, as so much in politics is.

The creationists cut at the very credibility of science when they cast doubt on our methods. When they do that, they make it easier to distort scientific findings in controversial policy areas.

We can see that happening right now with issues like stem cells, abortion, global warming and missile defense. When the testing of the proposed missile defense system showed it didn't work, the Pentagon's answer, more or less, went, "No more tests before we build it."

"We live in a society where it's considered okay for intelligent people to be scientifically illiterate."

SA: Between your popular writing and your political work, when do you do science?

LK: In the quiet hours of the night, in between those things. I do it then—or when I have the opportunity to sit down with students and postdocs. It's amazing to me, when we do that, how much we can accomplish. I rely on that a lot lately.

There can be months when I'm working on other things, and I get very, very depressed. Talking about science is important, and it may be the most important thing that I do. But if I'm not actually doing science, I feel like a fraud. On the other hand, if I don't do the public stuff, I also feel like a fraud.

SA: Why a fraud?

LK: Because science is not done in a vacuum. It is done in a social context, and the results of science have important implications for society, even if it is simply providing a general understanding of how we humans fit into the cosmos.

Thus, simply producing new knowledge, without making any attempt to help disseminate it and explain it, is not enough. I think one cannot expect every scientist to spend time on the effort to explain science. But in a society in which the science is of vital importance and also in which many forces are trying to distort the results of science, it is crucial that some of us speak out. SA

Arsenic in drinking water could severely poison 50 million people worldwide. Strategies being tested in Bangladesh might help prevent the problem

ARSENIC CRISIS in Bangladesh

By A. Mushtaque R. Chowdhury
Photography by Dilip Mehta

ARSENIC FLOWS from a tubewell in Bilkada village in Bangladesh. Farmer Abdul Rahman, whose foot was amputated after cancer caused by the contaminated water, looks on as a neighbor pumps.

A cold, clear, sparkling flow gushes from the tubewell where Pinjra Begum used to collect drinking water for her family. Married at age 15 to a millworker, she had made a pretty bride. Soon, however, her skin began to turn blotchy, then ultimately gangrenous and repulsive. Her husband remarried. In 2000 she died of cancer, at 26 years of age, leaving three children.

Pinjra Begum was poisoned by the beautiful water she had faithfully pumped. In the 1970s and 1980s the Bangladesh government, along with international aid agencies spearheaded by UNICEF, undertook an ambitious project to bring clean water to the nation's villages. Too many children were dying of diarrhea from drinking surface water contaminated with bacteria. The preferred solution was a tubewell: a simple, hardy, hand-operated pump that sucks water, through a pipe, from a shallow underground aquifer. The well-to-do could afford them, and with easy loans from nongovernmental agencies, many of the poor also installed the contraptions in their courtyards. A tubewell became a prized possession: it lessened the burden on women, who no longer had to trek long distances with their pots and pails; it reduced the dependence on better-off neighbors; and most important, it provided pathogen-free water to drink. By the early 1990s 95 percent of Bangladesh's population had access to "safe" water, virtually all of it through the country's more than 10 million tubewells—a rare success story in the otherwise impoverished nation.

Alas, somebody—everybody—neglected to check the water for arsenic. As early as 1983, dermatologist Kshitish C. Saha of the School of Tropical Medicine in neighboring Kolkata (Calcutta), India, had identified the skin lesions on some patients as arising from arsenic poisoning. He traced the mineral to water from tubewells. The patients were mostly from the eastern Indian state of West Bengal, which shares some aquifers with Bangladesh; more pointedly, some were immigrants from Bangladesh. Over the next few years, environmental scientist Dipankar Chakraborti of Jadavpur University in Kolkata established that many aquifers in West Bengal were severely contaminated with arsenic. Yet the British Geological Survey (BGS) conducted an extensive test of Bangladesh's water supply in 1993 and pronounced it safe, not having tested for arsenic. That same year Abdul W. Khan of the Department of Public Health Engineering in Bangladesh discovered the mineral in tubewell water in the western district of Nawabganj.

ABANDONED by her husband, Ambia Khatum, with her daughter, displays characteristic sores. Lesions on the palms and soles make daily chores painful.

DILIP MEHTA *Contact Press Images*

Today around 30 percent of Bangladesh's tubewells are known to yield more than 50 micrograms of arsenic per liter of water, with 5 to 10 percent providing more than six times this amount. The Bangladesh government specifies more than 50 micrograms per liter as being dangerous. (I use this standard in the article. The World Health Organization's upper limit, which is also the recently revised standard of the U.S. Environmental Protection Agency, is 10 micrograms. Unfortunately, this amount is too small to test for accurately in the field.) That means at least 35 million people—almost one quarter of the population—are drinking potentially fatal levels of arsenic.

Another concern is that Bangladeshis may be ingesting arsenic through a second route: the grain they eat two or three times a day. In the dry months, rice fields are irrigated with pumped underground water. Recently researchers from the University of Aberdeen in Scotland found that the arsenic content of local rice varies from 50 to 180 parts per billion, depending on the rice variety and on where it is grown. (Fifty parts per billion is the equivalent of 50 micrograms per liter in water.) A few vegetables, in particular an edible tuber containing an astonishing 100 parts per *million* of arsenic, are also contaminated. Hardly any guidelines exist as to what levels of arsenic in food might be dangerous.

And Bangladesh is not alone. The mineral occurs in the water supply of communities in diverse countries, such as India, Nepal, Vietnam, China, Argentina, Mexico, Chile, Taiwan, Mongolia and the U.S. [*see map on opposite page*]. As many as 50 million people worldwide could be severely affected eventually. Arsenic in drinking water thus constitutes the largest case of mass poisoning in history, dwarfing Chernobyl.

Mineral Water

THE FIRST SIGN of poisoning, which may appear as long as 10 years after someone starts drinking arsenic-laden water, is black spots on the upper chest, back and arms, known as melanosis. Palms of the hands or soles of the feet become hard and lose sensation (keratosis). The patient may also suffer from conjunctivitis, bronchitis and, at very high concentrations of arsenic, diarrhea and abdominal pain. These symptoms describe the first stage of arsenicosis, as arsenic-induced ailments are known. In the second stage, white spots appear mixed up with the black (leucomelanosis), legs swell, and the palms and soles crack and bleed (hyperkeratosis). These sores, which are highly characteristic of arsenic poisoning, are painful and can become infected; they make working and walking difficult. In addition, neural problems appear in the hands and legs, and the kidneys and liver start to malfunction. In the third stage the sores turn gangrenous, kidneys or liver may give way, and in around 20 years, cancers show up.

Pinjra Begum died unusually young; she may have been drinking high levels of arsenic since childhood. One study in Taiwan found that drinking 500 micrograms of arsenic per liter of water led to skin cancer in one out of 10 individuals. The major cause of death, however, is internal cancers, especially of the bladder, kidney, liver and lung. A 1998 study in northern Chile attributed 5 to 10 percent of all deaths in those older than 30 to arsenic-induced internal cancers. These people were exposed, at least initially, to around 500 micrograms per liter. The U.S. National Research Council concluded in 1999 that the combined cancer risk from ingesting more than 50 micrograms of arsenic per liter of water could easily lead to one in 100 people dying of cancer.

Drinking water with high levels of arsenic can also lead to neurological and cardiovascular complications. The extent of poisoning depends on the dose and duration of exposure, interactions of the arsenic with other dietary elements, and the age and sex of the individual. So far no one knows the true impact of the poison in Bangladesh. Anecdotal evidence suggests tens of thousands of cases of arsenicosis and reports a "large number" of deaths. Although a few cancer cases are seen, this epidemic has yet to peak.

Unfortunately, the Bangladesh health system is unprepared for a crisis of this magnitude. Health workers can offer ointments to relieve the pain of lesions and to prevent infection, and gangrenous limbs can be amputated, but chronic arsenic poisoning has no real remedy. One suggested treatment, chelation, requires the patient to ingest a chemical that binds to arsenic and aids its excretion. Yet chelation is of limited value, because even without it the body ejects arsenic quite efficiently; besides, the patient could go right back to ingesting contaminated water. Drinking safe water, on the other hand, seems to dispel the early symptoms of arsenicosis. But providing such water is not as easy as it sounds.

The source of—and perhaps the solution to—Bangladesh's arsenic problem lies under the ground. The nation is largely a delta, formed by silt deposited over 250 million years by two great Himalayan rivers, the Ganga and the Brahmaputra. In some areas, the sediment layer is as much as 20 kilometers deep. Most of the poisoned aquifers are shallow, however, from 10 to 70 meters deep, and lie to the south and southeast of the country. The BGS notes that around 18,000 years ago, when the sea level dropped by around 100 meters, the rivers cut deep channels into the existing sediment. In later years, these valleys filled up with a gray clay that seems to hold the poison. Older, brown alluvium, such as in the northwest or the hilly regions, is less contaminated.

An early hypothesis by Chakraborti holds that the arsenic is associated with iron pyrites and enters the aquifers by an oxidation process. So overuse of groundwater, mainly for irrigation, lowers the water tables, allowing air to reach the contaminated clay and release the arsenic. By this theory, human activity is aggravating the arsenic problem. Nowadays a rival hypothesis, that of reduction, has gained currency. According to the BGS, the arsenic is adsorbed onto particles of iron oxyhydroxide, which are reduced by organic extracts in the water itself, releasing arsenic. If so, the mineral has always been in the water. Controversy continues to rage, however: Chakraborti asserts that some tubewells he measured to be arsenic-free a decade ago are now poisoned, suggesting that complex geochemical processes are even now under way.

In response to the crisis, the government created the Bangladesh Arsenic Mitigation and Water Supply Project in 1998, to which effort the World Bank provided a loan of $32.5 million. Much of this money still lies unused because of fundamental uncertainties in how to proceed. The Bangladesh Rural Advancement Committee (BRAC), a nongovernmental organization of which I am a deputy executive director, has, however, been working since 1997 to find an answer to the arsenic dilemma.

Face Forward

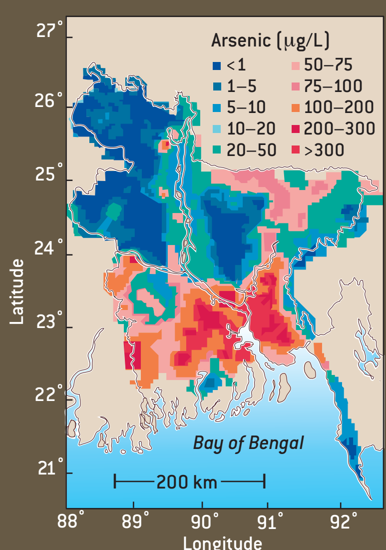
INITIALLY VILLAGERS in the two regions where we researched solutions to the arsenic problem—Sonargaon to the east and Jhikargacha to the west—would

THE DISTRIBUTION OF ARSENIC

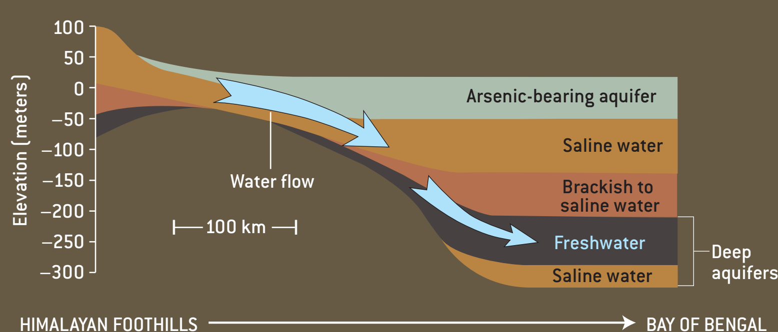
Arsenic is found in aquifers, usually underlying river deltas, around the world (*red areas at right*). In Bangladesh, arsenic levels are highest in the south (*bottom left*), presumably because the arsenic accumulated there when the Ganga and Brahmaputra rivers washed soil down from the Himalayas to the Bay of Bengal. The arsenic, which occurs in more recent, shallow deposits of clay, dissolves in underground water by processes that remain disputed. Aquifers deeper than 200 meters are believed to be free of the mineral (*bottom right*).

WORLDWIDE RISK

BANGLADESH



NORTH-SOUTH CUT THROUGH BANGLADESH DELTA



LUCY READING AND JANA BRENNING; SOURCE: "ARSENIC CONTAMINATION IN SOUTH-EAST ASIA REGION: TECHNOLOGIES FOR ARSENIC MITIGATION," BY M. FEROZE AHMED IN THE WORLD BANK GROUP'S "WATER WEEK 2004" FORUM

TWO WIVES of Abdul Rahman, the bedridden Haliman—a victim of the arsenic epidemic—and her young replacement, Shazida, have no choice but to get along. Shazida runs the household and takes care of Haliman's children.

DILIP MEHTA *Contact Press Images*

scarcely believe that their health problems arose from their precious tubewells. To ensure their cooperation, BRAC trained about 160 village women, even some who were illiterate, to test tubewell water using field kits. The volunteers tested more than 50,000 tubewells, painting red those that gave more than 50 micrograms of arsenic per liter and green those that gave less. We confirmed that they had identified 85 to 90 percent of the wells correctly. In some villages, all the tubewells turned out to be poisoned. In others, none were. Peculiarly, one tubewell might prove dangerous, whereas another close by would be fine.

The volunteers learned to identify those with skin lesions and other obvious signs of arsenicosis and to distinguish the three stages of the ailment. They found approximately 400 victims, who were subsequently examined by doctors. About three quarters of the patients were in the initial stage, but only a few had developed cancer. Most—60 percent—were male, with an average age of 36 years. Some were as young as five. Observing the volunteers test tubewells and identify sufferers, everyone in the targeted villages became aware of this previously unknown problem.

The volunteers also worked closely with other community members and BRAC personnel to create maps that showed local sources of water—arsenic-free tubewells, ordinary wells, streams and ponds—that could possibly replace contaminated tubewells. We then tested various systems with an eye toward safety, efficacy, cost and social acceptability. Broadly, these options were water from ponds, rivers and wells treated to remove pathogens; rainwater; groundwater treated to remove arsenic; piped water; and water from very deep aquifers. Over the past few years, we have learned much about which solutions might work on a national scale. (In recognition of its contributions toward the health and development of the poor, BRAC recently received the Gates Award for Global Health, a sum of $1 million.)

Compelling reasons exist for promoting the use of surface water. It is plentiful and generally free of arsenic, down to a depth of 10 meters. Historically, the people of Bangladesh drank water from designated clean ponds. With the advent of tubewells, these ponds were neglected, filled up for building or diverted to fish culture. The pond sand filter—a sand-based system installed on the bank to remove mud and pathogens—aims to revive the use of such ponds. Unfortunately, the bacterial load is so high that although the filter reduces it by two orders of magnitude, the water still contains some contaminants. The main obstacle to this filter, however, is that most of the ponds are now employed for fish culture, and they contain toxic chemicals used for killing predatory species (before fry are released). The biocides dissipate, but the water remains unsafe for human consumption. Moreover, the community must commit to cleaning the filter every few months.

Ordinary wells also use surface water, in this case collected from within a deep hole; it normally contains few pathogens but can get contaminated with fecal matter. In contrast, rainwater is pure but not available year-round. We once thought the so-called three-pitcher method to be a brilliant idea; this simple household device filters tubewell water through two earthenware pots—containing sand, charcoal and, most important, iron chips for binding arsenic—so that safe water collects in the third pot. But the contaminated shavings need to be disposed of periodically, which is yet another problem. Larger-scale arsenic filters are expensive, and they, too, must be cleaned of poisonous sludge.

In conversations with villagers, we realized that although they want arsenic-free water, they do not want to feel that they are going back in time to methods they once discarded. Tubewells had fitted nicely with their forward-looking aspirations. In my view, any successful method must embrace this sentiment. The two options that meet this criterion are piped water and deep wells.

Over the past few years, BRAC and other organizations have implemented a pilot program to pipe water, treated at a centralized facility, to villages. People welcomed it. A recent study by BRAC, in collaboration with the World Bank, found

THE AUTHOR

A. MUSHTAQUE R. CHOWDHURY has been involved with the Bangladesh Rural Advancement Committee, one of the world's largest and most successful private development organizations, since 1977. He is the founder of its research and evaluation division and directs its arsenic mitigation effort. Born in Bangladesh, Chowdhury received his early education in Dhaka and his Ph.D. from the London School of Hygiene and Tropical Medicine in 1986. He has written extensively on health issues in the developing world. Chowdhury serves as co-chair of the U.N. Millennium Project's task force on child and maternal health and is currently a visiting professor at Columbia University.

that villagers are even willing to pay part of the cost for installation. Nevertheless, the price remains prohibitive, and implementing such a program more broadly requires organization. If Bangladesh decides to move ahead with such systems, even on a limited scale, the local government must be charged with maintaining them in conjunction with nongovernmental organizations.

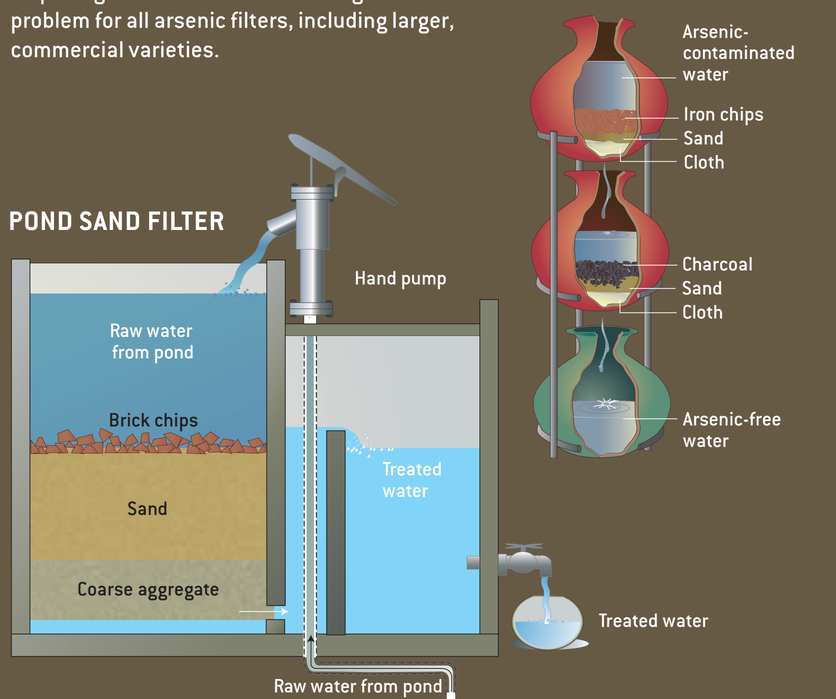
The long-term solution might instead lie in deep tubewells, which extract water from aquifers 200 meters or farther underground. Much of Bangladesh consists of two overlying freshwater aquifers, a shallow one (which reaches down as far as 70 meters) separated from a deeper one by layers of clay. Geologists agree that the risk of arsenic in deep aquifers is low, but before a few million such tubewells are dug, they need to be absolutely sure. Moreover, the drilling process needs to be refined so that the deeper aquifers are not poisoned by arsenic-bearing water trickling down from the shallow aquifers through the boreholes themselves.

Such drilling technology is untested, and digging these wells will require expert guidance. Murphy's Law—if anything can go wrong, it will—seems to apply with particular vengeance in developing countries, as the arsenic problem itself indicates. So the risk of inadvertently contaminating the deep aquifers must be carefully weighed.

CHEAP SOLUTIONS FOR SAFER WATER

No perfect technology exists for providing safe water to poor communities plagued by the arsenic problem. Surface water in Bangladesh is free of arsenic but highly compromised by disease agents. The pond sand filter reduces the pathogens in pond or river water by two orders of magnitude—which is not enough. The three-pitcher method is simple and cheap: it removes arsenic from tubewell water by passing it through iron shavings. Unfortunately, disposing of the contaminated sludge is a problem for all arsenic filters, including larger, commercial varieties.

THREE-PITCHER FILTER



LUCY READING; SOURCE: SHARIAR SHAMS, WITH MODIFICATION BY MOHAMMAD JAKARIYA *BRAC*

Money Matters

RESEARCHERS AT Columbia University recently estimated that approximately $290 million will fund an integrated five-year testing, mitigation and monitoring program for arsenic all over Bangladesh. This amount, which envisages a deep tubewell in each of the country's 86,000 villages, is not too large for the benefit that will accrue, but it may be more than Bangladesh alone can afford.

Even if the money can be found, choosing and implementing a permanent solution to the arsenic problem will take several years. And Bangladesh cannot afford to wait. The country must immediately embark on a project to identify patients and provide them with safer water, in whatever way is locally feasible. In addition, we need to test every tubewell in the country. Despite everyone's best efforts, at the current rate of testing it could take several years to cover the entire nation.

In truth, even the poorest nations—perhaps especially the poorest—should check the quality of their water constantly. Ignoring this imperative is what landed Bangladesh in this predicament in the first place. Monitoring—not only for arsenic but also for manganese, fluoride, pesticides, other chemicals and pathogens—must become routine in all regions of the world where people drink water from underground. SA

MORE TO EXPLORE

Combating a Deadly Menace: Early Experiences with a Community-Based Arsenic Mitigation Project in Bangladesh. A. Mushtaque R. Chowdhury et. al. Bangladesh Rural Advancement Committee Research Monograph Series, No. 16, August 2000.

Contamination of Drinking-Water by Arsenic in Bangladesh: A Public Health Emergency. Allan H. Smith, Elena O. Lingas and Mahfuzar Rahman in *Bulletin of the World Health Organization,* Vol. 78, No. 9, pages 1093–1103; September 2000. Available at **www.who.int/docstore/bulletin/pdf/2000/issue9/bu0751.pdf**

Arsenic Contamination of Groundwater in Bangladesh, Vols. 1–4. Edited by D. G. Kinniburgh and P. L. Smedley. British Geological Survey Technical Report WC/00/19, 2001. Available at **www.bgs.ac.uk/arsenic/Bangladesh/**

Gates Award for Global Health, 2004, to BRAC. Award speech is available at **www.gatesfoundation.org/MediaCenter/Speeches/BillSrSpeeches/BGSSpeech-GatesAwardGH040603.htm**

MEDICAL IMAGING

Seeing Inside

Medical imaging helps doctors see injuries and disease directly, so they don't have to rely on external exams or exploratory surgeries. Several tomography techniques have spread widely. In each case, a patient lies on a bed inside a doughnut-shaped machine. Hardware takes images of numerous two-dimensional slices of the person's body, and a computer assembles them into a three-dimensional picture.

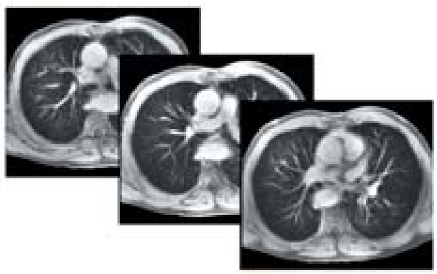
Computed tomography (CT), which creates images with x-rays, is good at showing sharp contrasts in bone and tissue density, indicating broken bones, blood clots and kidney stones. Early machines of the 1970s required five minutes to render a slice 10 millimeters across; today resolution is one millimeter, and a slice takes only one second. If machine cost and speed improve only a bit further, CT could also take over most standard x-ray procedures, says C. Carl Jaffe, professor of internal medicine at Yale University.

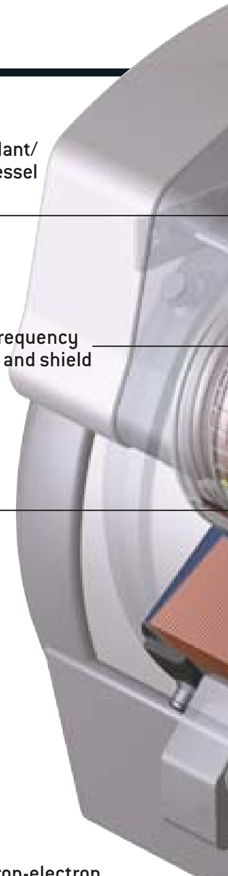
In positron emission tomography (PET), a patient is injected with a radioactive element that produces photons, which are sensed slice by slice. Because the element binds to molecules such as glucose, the emissions reveal the relative rates at which cells consume these molecules, a marker of cell metabolism. Unusual activity can indicate cancer cells, neurological diseases such as Alzheimer's, the malignancy of tumors, and brain activity during mental processes.

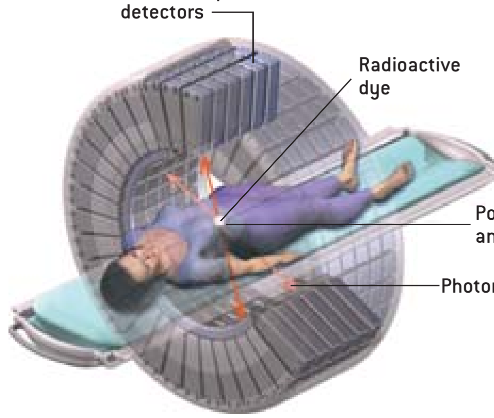
Magnetic resonance imaging (MRI) detects subtle fluctuations in the magnetic properties of hydrogen nuclei. The resulting image shows varying tissue density, which reveals injuries such as torn cartilage and herniated disks, as well as tumors. A research format called functional MRI detects how rapidly cells are consuming oxygen—an indicator of which neurons in the brain are active during perception or thinking.

As engineering improves, hybrid machines "are taking the market by storm," Jaffe says. A CT-PET machine can combine images to distinguish, for example, between a cancerous growth and a routine fibrous mass. The next advance will be software algorithms that can assess what is happening in tissue, not just assemble a picture of it. "We will no longer have to rely solely on what we see," Jaffe says, "but what the raw data actually indicate." —*Mark Fischetti*

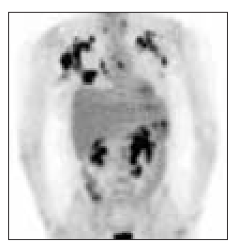
TOMOGRAPHY machines image thin cross sections of tissue (*below, a heart*). Software combines many adjacent slices to form a three-dimensional picture.







PET: Radioactive elements such as oxygen or carbon tag desired molecules, such as sugar, that different tissue cells consume at varying rates. The elements emit positrons; when one meets an electron, the pair annihilates, sending off two 511-kilo-electron-volt (keV) photons at 180 degrees. When photomultipliers opposite each other sense photons simultaneously, that event defines a line through the emitting cell. Many intersecting lines define cells in a given slice and their rate of metabolism. *At right:* Cancer cells growing in lymph nodes (*top left* and *right*).



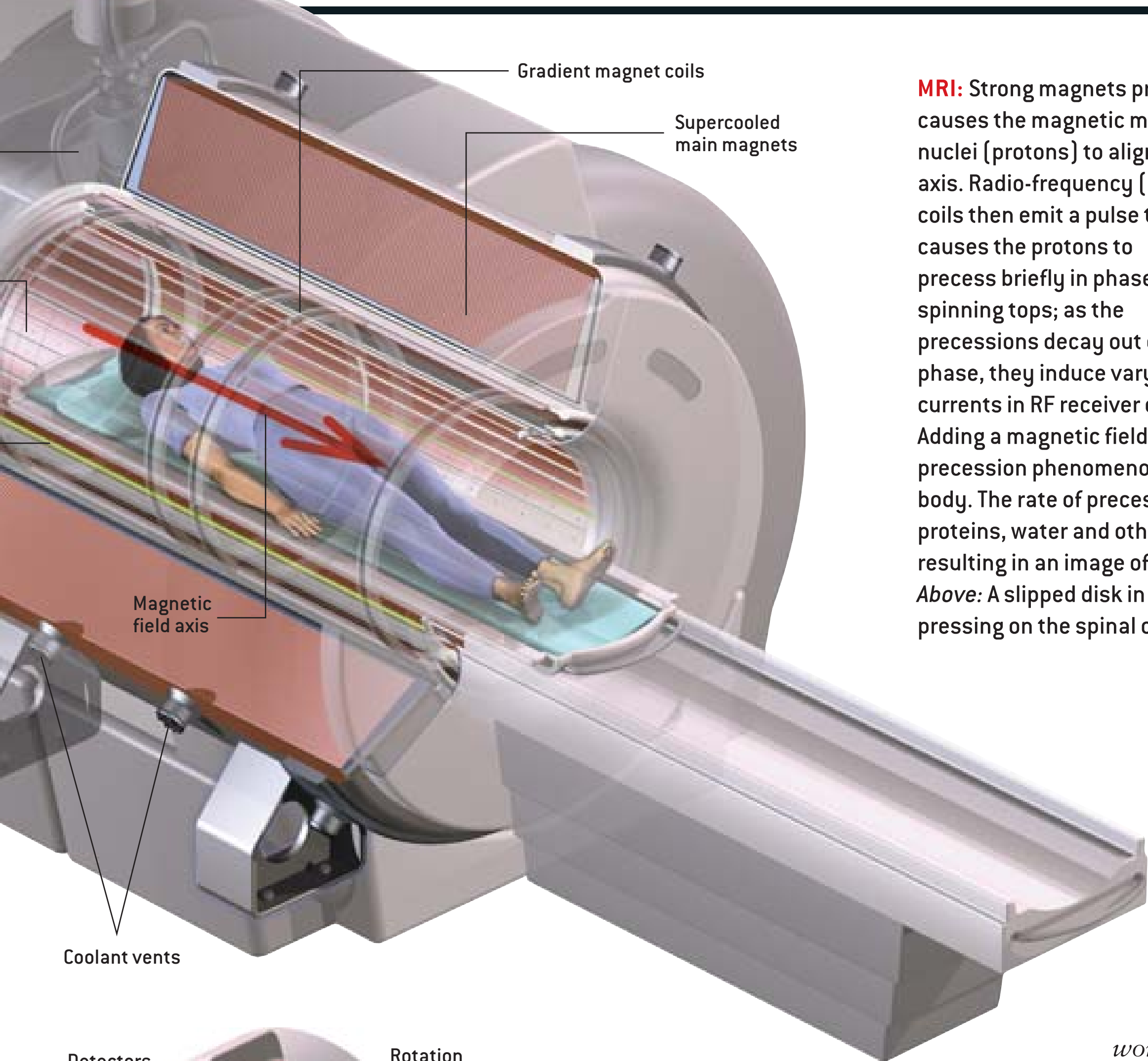
GRIFF WASON (*illustrations*); ZEPHYR/SCIENCE PHOTO LIBRARY (*MRI cross sections*); REPRINTED FROM breastcancer.org AND IMAGE COURTESY OF NATIONAL MEDICAL IMAGING, PHILADELPHIA (*PET scan*); P. MARAZZI/SPL (*MRI scan*); DU CANE MEDICAL IMAGING/SPL (*CT scan*)

DID YOU KNOW . . .

➤ NAME GAME: Computed tomography (CT) was originally called computed axial tomography (CAT), because the x-ray slices were taken along a single plane. But newer machines can operate on various planes, voiding the cuddly label. Magnetic resonance imaging (MRI) began as nuclear magnetic resonance (NMR), because it senses changes in nuclei. The public took "nuclear" to mean scary radiation, however, and the medical community euphemized the term.

➤ ELECTRIC VIEW: An MRI exam might one day specify which chains of neurons are communicating during mental activity, not just which cells are metabolically active. Michael Joy, professor of biomedical engineering at the University of Toronto, has developed MRI-based "current density imaging," which he expects will sense depolarization—when neurons open membrane channels that allow signaling ions to flow between cells. Joy is also using MRI to track the path that charge takes through tissue, which could diagram how a defibrillator current shoots through a failed heart and how deep-brain stimulation flows through the brain of a Parkinson's patient.

➤ ULTRASOUND: A handheld ultrasound unit placed against a patient's skin sends high-frequency sound waves into the body and measures the echoes, creating a low-resolution but real-time moving image of internal organs or a fetus. Ultrasound is sometimes not defined as tomography, though, because it does not assemble slices.



MRI: Strong magnets produce a uniform field that causes the magnetic moments, or spins, of hydrogen nuclei (protons) to align preferentially along the field axis. Radio-frequency (RF) coils then emit a pulse that causes the protons to precess briefly in phase like spinning tops; as the precessions decay out of phase, they induce varying currents in RF receiver coils. Adding a magnetic field gradient confines the precession phenomenon to a precise slice of the body. The rate of precession decay varies for fats, proteins, water and other hydrogen-rich molecules, resulting in an image of tissue types and densities. *Above:* A slipped disk in the neck (*fourth from top*) pressing on the spinal cord.

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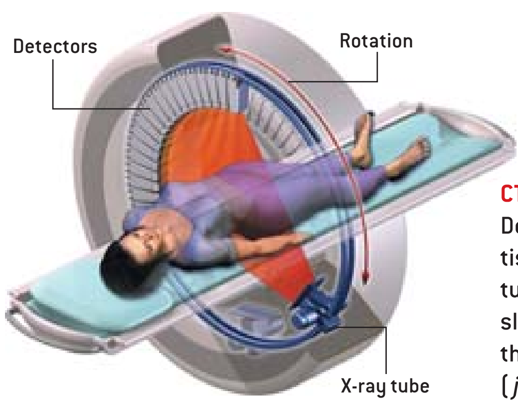


CT: A tube sends a plane of 140-keV x-rays through the body. Detectors sense the attenuation of rays, which different tissue densities absorb and deflect to a given degree. The tube and detectors rotate in tandem to complete one image slice. The bed advances the patient several centimeters, and the process repeats, over and over. *At right:* A large blood clot (*just below circle at center*) in the lung's pulmonary artery.

TECHNICALITIES

Crippled but Not Crashed

NEURAL NETWORKS CAN HELP PILOTS LAND DAMAGED PLANES **BY MIKE CORDER**

On July 19, 1989, as United Airlines flight 232 cruised over Iowa, the fan disk of the tail engine on the DC-10 broke apart, and the debris cut through all three of the plane's hydraulic lines. Because the pilots could not move any of the jet's control surfaces—the ailerons on the wings and the elevators and rudder on the tail—a horrific crash seemed inevitable. But by carefully adjusting power to the two remaining engines, the crew managed to maneuver the plane to the Sioux City airport. Although the jet flipped over and caught fire after hitting the runway, 184 of the 296 passengers and crew members survived.

The pilots of flight 232 proved that it was possible to control a modern airliner using only the engines. And this discovery led some innovative engineers to wonder if they could program flight computers to achieve the same feat, making it easier for a crew to safely land a heavily damaged aircraft. This research has been gradually progressing over the past 15 years, and the technology could be incorporated into commercial and military planes in the not too distant future. To judge how well these computer-controlled flight systems perform, I decided to see if they could enable a moderately experienced pilot like myself to fly a crippled jet.

But first, a little background. On early aircraft, the control stick and rudder pedals were directly connected to the control surfaces with wires or rods or cables. But as planes got faster and larger, pilots found it hard to move the stick. So engineers added "power steering," connecting the cables to hydraulic servos that amplify the pilot's efforts. Then, with the advent of the digital age, aircraft makers developed control systems that feed the input from pilots into a computer. This so-called fly-by-wire system can greatly improve an airplane's performance. For example, a fighter jet may fly well when lightly loaded but not so well when it carries bombs on its wings. With a computer in the loop, the control rules can be modified to make the plane behave more consistently. Fly-by-wire also allows the creation of safeguards: if a pilot tries to do something that would cause the aircraft to break apart or plummet to the ground, the computer can ignore the inputs and take the plane only to the edge of the flight envelope.

Shortly after the crash of flight 232, Frank W. (Bill) Burcham, Jr., then chief propulsion engineer at the NASA Dryden Flight Research Center in Edwards, Calif., began an effort to develop software that would enable jet engines to compensate for damage to a plane's control surfaces. Initially the research was considered too far-out to be funded, but a few engineers at Dryden volunteered their spare time. The project, which became known as Propulsion Controlled Aircraft (PCA), eventually received a small budget and proceeded to flight tests with an MD-11 jet. On August 29, 1995, the PCA team brought the plane in for a smooth landing at Edwards Air Force Base using only the computer-controlled engines to maneuver the craft. The NASA engineers felt they had demonstrated that airliner safety

INTELLIGENT FLIGHT CONTROL has been tested in the mock cockpit (*left*) of the Advanced Concepts Flight Simulator (*above*) at the NASA Ames Research Center in California.

TOM TROWER *NASA Ames Research Center*

could be significantly enhanced just by modifying a plane's software. Unfortunately, none of the aircraft manufacturers chose to adopt the technology.

A few years later researchers in the Intelligent Flight Control (IFC) group at the NASA Ames Research Center in Mountain View, Calif., followed up on the PCA work by developing a system that would allow the computer-controlled engines of a damaged aircraft to work together with any control surfaces that remain functional. The system is based on neural-network software, which mimics the behavior of the human brain by learning from experience—the network's connections strengthen with use and weaken with disuse. The neural networks in the IFC system compare the way the plane should be flying with the way it actually is flying. Differences may be caused by inaccuracies in the reference model, normal wear and tear on the plane, or damage to the aircraft's physical structure. The networks monitor these differences and attempt to minimize them.

For example, if you want to make an undamaged airplane climb, you pull back on the control stick, which raises the elevators. But if the elevators are not working, the IFC system will raise both ailerons to lift the airplane's nose. (Ailerons typically move asymmetrically, with one rising as the other falls.) If this maneuver does not correct the error or if it reaches the limits imposed to prevent the aircraft from rolling over, the IFC system uses the thrust of the engines to achieve the desired pitch.

The Ames researchers tested their system by inviting professional airline pilots and NASA test pilots to fly in the lab's simulator. First, the pilots operated the simulated aircraft under normal conditions. Then the researchers mimicked a variety of failures and observed how the pilots reacted using different types of control systems. In almost every case, the IFC system performed better than a conventional fly-by-wire control system. When the engineers simulated the failure of all tail controls, only half the pilots could safely land the plane using the fly-by-wire system, but all of them made it back to the runway using IFC.

So what's it like to fly a plane equipped with neural networks? At the invitation of Karen Gundy-Burlet, head of the IFC group, I recently spent several hours in its lab to see the system firsthand. I am a private pilot with no experience flying larger aircraft. The IFC simulator was set up to represent a very big plane: the U.S. Air Force's four-engine C-17 transport jet. The simulator features a large wraparound screen to show the animated landscape and a mockup of a glass cockpit, which replaces the traditional flight gauges with flat-panel color displays.

FIRST FLIGHT TESTS of the Intelligent Flight Control system are being conducted in a modified F-15 fighter jet at Edwards Air Force Base.

JIM ROSS NASA Dryden Flight Research Center

Gundy-Burlet set me up on a 12-mile final approach to the San Francisco airport and let me embarrass myself trying to get an undamaged plane to the ground. Don Bryant, a retired U.S. Navy fighter pilot who works with the IFC group, was polite enough not to openly laugh at my ham-handed attempts to control the craft. My biggest problem was my unfamiliarity with the glass cockpit, which is only now starting to appear in private planes. I spent more time staring at the simulated display trying to find familiar values such as airspeed and altitude than I did actually flying the aircraft. That said, I got a basic feel for how the undamaged plane flew.

Then Gundy-Burlet reset the simulator to the initial location and said, "Captain, I'm sorry, but you've lost all the control surfaces on the tail." Both the elevators and rudders were inoperative, which would probably be a death sentence for an amateur pilot in the real world. But I was pleasantly surprised to find that the simulated aircraft was pretty controllable. I made a few gentle turns to get a feel for the plane while also trying to stay on the right heading. The damaged jet was sluggish in roll and pitch, but its behavior seemed more natural once I slowed down my steering. This change was undoubtedly facilitated by the neural networks, which were training themselves to compensate for the damage. As the networks adjusted to the new conditions, the plane kept getting easier to fly. Within a few minutes, I was able to safely land the simulated craft, although it did stray from the runway.

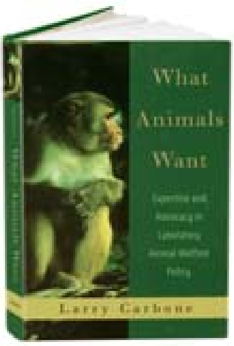
The overall experience was fairly tame, almost ordinary. It was only later that I recognized the true magnitude of this advance. A private pilot who had never flown a large aircraft was able to land a heavily damaged four-engine jet without killing anybody (in a simulation, at least).

How quickly might this technology see actual use? NASA researchers plan to flight-test the IFC system on F-15 fighter jets and C-17 transport craft over the next two years. The earliest adopters will most likely be the makers of military aircraft. Damage-compensating flight controls should be particularly useful to pilots who fly aircraft that get shot at from time to time. SA

Mike Corder is a freelance writer in Santa Cruz, Calif., who is building a Van's Aircraft RV-7A plane in his spare time.

Speaking for the Animals

A VETERINARIAN ANALYZES THE TURF BATTLES THAT HAVE TRANSFORMED THE ANIMAL LABORATORY **BY MADHUSREE MUKERJEE**



WHAT ANIMALS WANT: EXPERTISE AND ADVOCACY IN LABORATORY ANIMAL WELFARE POLICY
by Larry Carbone
Oxford University Press, New York, 2004 ($35)

The one time I saw the inside of an animal laboratory, at a prestigious university, the veterinarian who showed me around was subsequently fired for that transgression. So it is little surprise that Larry Carbone, a laboratory animal veterinarian, gives us few peeks behind the door: the book has virtually no anecdotes. Instead he takes off the lab's roof to offer a bird's-eye view—distant, measured and worded with sometimes excruciating care—of the battles raging within.

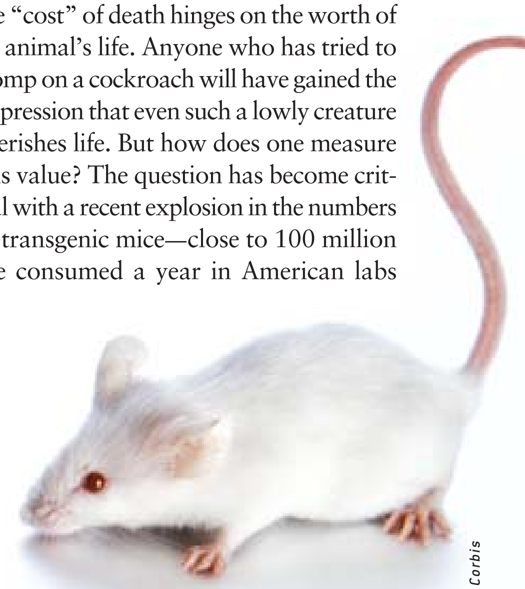
A veterinarian's oath binds her to "the benefit of society through the protection of animal health, the relief of animal suffering, the conservation of animal resources, the promotion of public health, and the advancement of medical knowledge." It imposes contradictory tasks on the laboratory animal veterinarian. "So you keep them healthy until the scientists can make them sick," Carbone quotes a skeptic as saying. A lab animal vet can please no one, it seems—certainly not the animal lover, who suspects her split loyalties, nor the animal researcher, who resents her attempts to oversee not just animal care but also experimental practice.

Carbone, who holds doctorates in veterinary medicine and in the history and philosophy of science, is a vet in the animal facility at the University of California at San Francisco. In early chapters of *What Animals Want*, he describes the unending philosophical debates over animal care and use, while in the more interesting later chapters he documents the jostling that determined the rather limited turf of the lab animal vet.

Laboratories first hired veterinarians in the 1930s, he explains, to assuage public concern over animal care and indeed restricted their duties to keeping animals healthy until needed. With the passage of the Animal Welfare Act in 1966, and its several amendments, veterinarians came to play a more central role. Today they run animal facilities, answer to federal inspectors (most of whom are themselves veterinarians), and advise on anesthesia and other aspects of research. Even so, Carbone notes that supervising veterinarians often cannot keep track of animals once they leave an institution's central animal facility for research. And whereas only veterinarians are authorized to perform surgery on pets, surgery in the lab may be entrusted to an inadequately trained student or technician. And no one is charged with weighing the potential benefits of a research project against the cost, in pain, suffering and death, to the animals.

Often the tug-of-war involves the question of what an animal feels. The chapter on mouse decapitation is fascinating, although I cannot recommend it as beachside (and certainly not bedside) reading. Many researchers prefer killing by decapitation, which contaminates tissues less than other methods do. Carbone details how a finding that brain waves in rats persist for up to half a minute after decapitation caused initial concern that the process entails intense pain. That interpretation was instantly smothered by a pile of papers pointing out that such brain waves could mean anything. Indeed, animals are assumed to feel pain in situations where a human would, and in this case we have no way of knowing. Revealingly, though, one paper argued that decapitation was "far too important a tool" to be rescinded on such a flimsy basis.

In truth, animal welfare legislation and public concern are both more focused on pain than on death itself. Philosophically, the "cost" of death hinges on the worth of an animal's life. Anyone who has tried to stomp on a cockroach will have gained the impression that even such a lowly creature cherishes life. But how does one measure this value? The question has become critical with a recent explosion in the numbers of transgenic mice—close to 100 million are consumed a year in American labs



NUMBER OF MICE consumed in U.S. laboratories every year has shot up to almost 100 million, of which three quarters are disposed of unused.

CHRIS COLLINS *Corbis*

alone. (In 1996 U.S. laboratories used around 20 million laboratory animals.) Three quarters of the mice are wasted, according to Andrew Rowan of the Humane Society of the United States: now that many institutions have their own breeding facilities, far more mice than needed are being born.

The fact that mice are small and virtually indistinguishable compounds the problem: they have become a "standardized animal" to a medical researcher, in the same way that a molecule is a fundamental unit to a chemist. One observer describes scientists using and discarding mice with as much thought as if they were tissues, of the nose-blowing kind. Carbone pleads for treating each mouse as an individual—for assuming its life has some value or for tailoring the dose of an anesthetic to a specific creature's need rather than to the statistically defined response of a "standardized" mouse. His task is made even harder by a 2002 amendment that took birds, rats and mice out of the definition of "animal" in the Animal Welfare Act: these creatures are not protected by federal law. They are not even counted.

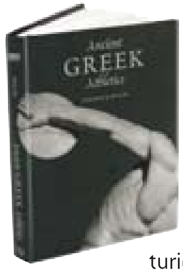
Most scientists take pride in being caring and sensitive, Carbone notes. Oddly, that can have its downside: "Protecting their self-identification as someone who would not hurt animals could lead these people, ironically, to refuse to see that their animals might indeed be in pain." For such reasons, he argues, laboratory animals should have an in-house advocate—and who better than the veterinarian? One can only hope that such a metamorphosis in her role will come sooner, rather than billions of mice later. SA

Madhusree Mukerjee has covered the use of animals in laboratories for this magazine, where she was an editor for seven years. She is author of The Land of Naked People: Encounters with Stone Age Islanders *(Houghton Mifflin, 2003).*

THE EDITORS **RECOMMEND**

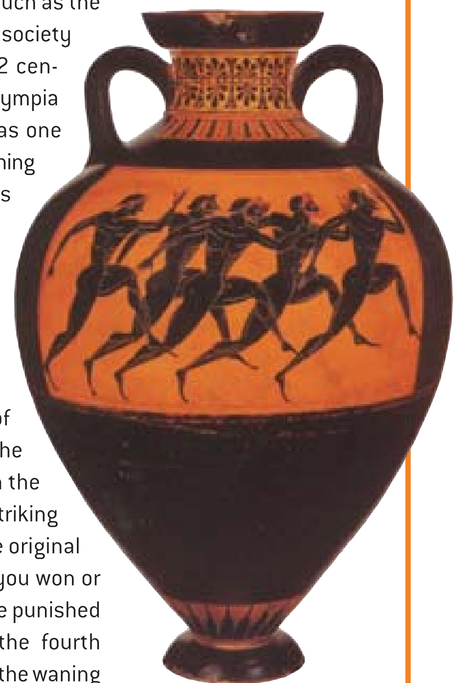
ANCIENT GREEK ATHLETICS

by Stephen G. Miller. Yale University Press, New Haven, Conn., 2004 ($35)



As the Olympic Games open in the land where it all began, it is both fitting and delightful to sit down with this beautiful, informative book. Miller, an archaeologist and professor of classics at the University of California at Berkeley, brings the ancient Greek athletic festivals to life by reconstructing the scene at one of the Panhellenic games and explores broader themes such as the integral role they played in society and politics. For almost 12 centuries, beginning in 776 B.C. at Olympia in the Peloponnese (not at Mount Olympus, as one often hears), the games were so popular that nothing was allowed to stand in the way; even battles were temporarily halted in deference to the athletic competition. Olympia was the site of only one of four major contests; the others were at Delphi, Isthmia and Nemea.

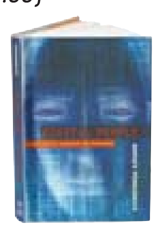
The closest visual link to the classic athletic festivals comes from paintings on amphoras, huge vessels that held as much as 39 liters of olive oil. These were offered as prizes at the games; one side depicted the event for which the prize was given. Modern fans would find other striking differences between today's contests and the original games: There were no second-place prizes—you won or you lost. There were no team sports. Fouls were punished by flogging. Athletes performed nude. By the fourth century A.D., with the spread of Christianity and the waning of belief in the Greek gods, the games "ceased completely to play any meaningful role in society." They were revived in something resembling their modern form in 1896.



RUNNERS on a fifth century B.C. amphora awarded to the winner of the race.

DIGITAL PEOPLE: FROM BIONIC HUMANS TO ANDROIDS

by Sidney Perkowitz. Joseph Henry Press, Washington, D.C., 2004 ($24.95)



Perkowitz, professor of physics at Emory University, takes the reader on an absorbing journey through the history of human efforts to duplicate human functions. Robots and artificial body parts represent the current level of achievement; the ultimate achievement may be artificial beings. Although "no one has yet made a completely autonomous being, or one that seems consistently and convincingly alive, or a bionic implant that improves human strength or wit … there is no doubt that existing technology will carry us further along these paths." And eventually we must face some profound questions. "What is our purpose in making artificial or hybrid beings? What are our ethical responsibilities toward them and theirs toward us? Do we have anything to fear from intelligent and powerful nonhuman beings?"

The books reviewed are available for purchase through www.sciam.com

COURTESY OF METROPOLITAN MUSEUM OF ART

One Hundred Years of Magnitude

THE EVER LENGTHENING CURRICULUM VITAE, AND VITA, OF ERNST MAYR **BY STEVE MIRSKY**

This month marks the publication of a new book, *What Makes Biology Unique?* (Cambridge University Press, 2004). Such philosophizing about science is inherently fascinating but in this case may be less interesting than the philosopher. The book is the 25th by Ernst Mayr, who was scheduled to add another significant achievement to his already prolific list shortly before this issue of *Scientific American* hit the newsstands: July 5 was Mayr's 100th birthday.

On May 10 the Museum of Comparative Zoology (MCZ) at Harvard University, Mayr's research home for the past 50 years, held a symposium/slightly premature–birthday bash in his honor. I arrived early and found the Geology Lecture Hall still mostly empty. A few minutes later an exceedingly elderly gent, not Ernst, slowly ambled in and did a cost-benefit analysis on the available seats. I overheard him say to no one in particular, "I need a place close enough so I can hear but not so close that I'll be a distraction when I fall asleep." This éminence grise was later introduced to the crowd as one of Mayr's former *students*.

James Hanken, director of the MCZ, began the program by noting that "this is only the latest in a string of milestones in the long and unique life and career of arguably the greatest evolutionary biologist of the 20th century." The greatest evolutionary biologist of the 19th century was Darwin, and that's it, folks, we're out of completed centuries during which evolutionary biology was a science.

In 1928 Mayr performed the first survey of the birds of New Guinea's Cyclops Mountains. Hanken recounted an anecdote that illustrates both the changed nature of biological fieldwork and Mayr's capacity for one-liners. It seems that Mayr and ornithologist Peter Alden attended a recent talk at Harvard by the naturalist and television host David Attenborough about Attenborough's attempts over many years to film bowerbirds and birds of paradise in New Guinea. "And after looking at all of these beautiful birds," Hanken said, "many of which are now endangered and highly prized and not to be even touched or breathed on, Ernst leaned over to Peter and said, 'I've eaten many of those.'"

One of the day's speakers, Mary Jane West-Eberhard of the Smithsonian Tropical Research Institute, never formally studied under Mayr but nonetheless described herself as an ipso facto student of Mayr, through reading, correspondence and conversation. Under that definition, Mayr's students number in the hundreds of thousands. She noted that for the auspicious occasion, "I thought of making a great big birthday cake. But then it occurred to me that a cake with that many candles might be regarded as a fire hazard and maybe a terrorist threat."

Mayr himself, nattily dressed and sporting a mischievous smile, expressed his "tremendous gratitude to so many people who made my life productive and enjoyable" and noted that many of those people didn't even know they were helping him. For example, he specifically thanked the woman in England who blackmailed Lord Walter Rothschild and drove him into the bankruptcy that in turn forced him to sell his bird collection to the American Museum of Natural History in New York City, where it became available for study by Mayr, who began working there in 1932.

During her talk, West-Eberhard revealed that Mayr had once shared with her one of his secrets for longevity, which was "to walk an hour a day, even when you're busy."

Ever a pragmatist, Mayr was clever enough to use time and not distance as the goal. If you live long enough, you can fulfill the hour requirement simply by walking to the mailbox, which is what Mayr was doing when I arrived at his home in Bedford, Mass., for a visit on the Saturday after the symposium. He spoke for almost two hours about modern biology, evolutionary theory and his scientific life. The transcript of that conversation has been posted on our Web site, www.sciam.com. Enjoy. SA

ILLUSTRATION BY MATT COLLINS; PHOTOGRAPH BY FRANK VERONSKY

What causes hiccups?

—J. Nowak, Torrevieja, Spain

William A. Whitelaw, a professor in the Respiratory Research Group at the University of Calgary in Alberta, explains:

Scientists have an incomplete understanding of what causes hiccups; they also do not know what purpose hiccups serve. A long list of medical disorders seems to be associated with hiccups. By far the most common are distension of the stomach and the resulting reflux of stomach acid into the esophagus. A disease or an irritation in the chest could be to blame. Hiccups may arise from a variety of neurological abnormalities, many of them involving the brain stem. Metabolic and other disorders, as well as medications that cause acid reflux, have also been linked to hiccups.

Several things happen in quick succession when a person experiences a hiccup. First the roof of the mouth lifts, as does the back of the tongue, often accompanied by a burp. Then the diaphragm and the entire set of muscles used for inhaling come together in a sudden, strong contraction. Just after that contraction begins, the vocal chords clamp shut, making the "hic" sound. The heart slows a bit. Hiccups tend to recur every few seconds, sometimes continuing for hours.

These observations imply that somewhere in the brain a central pattern generator, or CPG, exists for hiccups. In other words, we have a neural circuit designed for generating hiccups similar to those for actions such as breathing, coughing and walking. The hiccup CPG is most likely left over from a previous stage in evolution. A search through the animal kingdom for activity that resembles a hiccup turns up a few candidates. One is the CPG for gasping, a sudden intake of breath that can occur in rhythmic succession. In a recent paper, our research team argued that a better candidate is the CPG used by tadpoles for gill ventilation. Halfway through its development, a tadpole has both lungs that breathe air and gills that extract oxygen from water. The pressure-pump action of the tadpole's mouth at this stage is nearly the same action as hiccuping.

According to evolutionary theory, the CPG probably would not be preserved unless it served some purpose. One possibility is that the hiccup CPG directs suckling in infants, to ensure that milk does not get into the lungs. Another possibility is that the CPG controls burping to clear gas from an overfilled stomach.

How do sunless tanners work?

—F. Georgina, Fairbanks, Alaska

Randall R. Wickett, professor of pharmaceutics and cosmetic science at the University of Cincinnati College of Pharmacy, offers this explanation:

Sunless tanners dye skin darker by means of several chemical reactions. The active ingredient is the compound dihydroxyacetone (DHA). DHA is a sugar that reacts with proteins on the top layer of the skin, turning that layer brown. This process, known as the Maillard reaction, occurs frequently in food preparation and is responsible for the caramelization of sugars and the golden-brown color of beer. The tan formation sometimes emits a starchy odor that is difficult to mask with perfume.

The products of sunless tanning absorb a little less red light than skin pigments do when reacting with the sun, which can lead to orange coloration. Newer formulations use lower DHA concentrations, creating a tan that is more natural-looking. A number of products contain the sugar erythrulose, found in red berries, which adds a bit of red to the tone.

Sunless tanners are not without drawbacks. Color can be inconsistent if the product is applied unevenly. They offer no protection against sunburn and do not last as long as a real tan. Because only the uppermost layer of skin is stained and this layer is continually shed, it takes about three weeks for the tan to slough off; the use of exfoliating products speeds this process. SA

For a complete text of these and other answers from scientists in diverse fields, visit www.sciam.com/askexpert

SARA CHEN