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SCIENTIFIC AMERICAN

How to Protect **New Orleans** from Future Storms

FEBRUARY 2006
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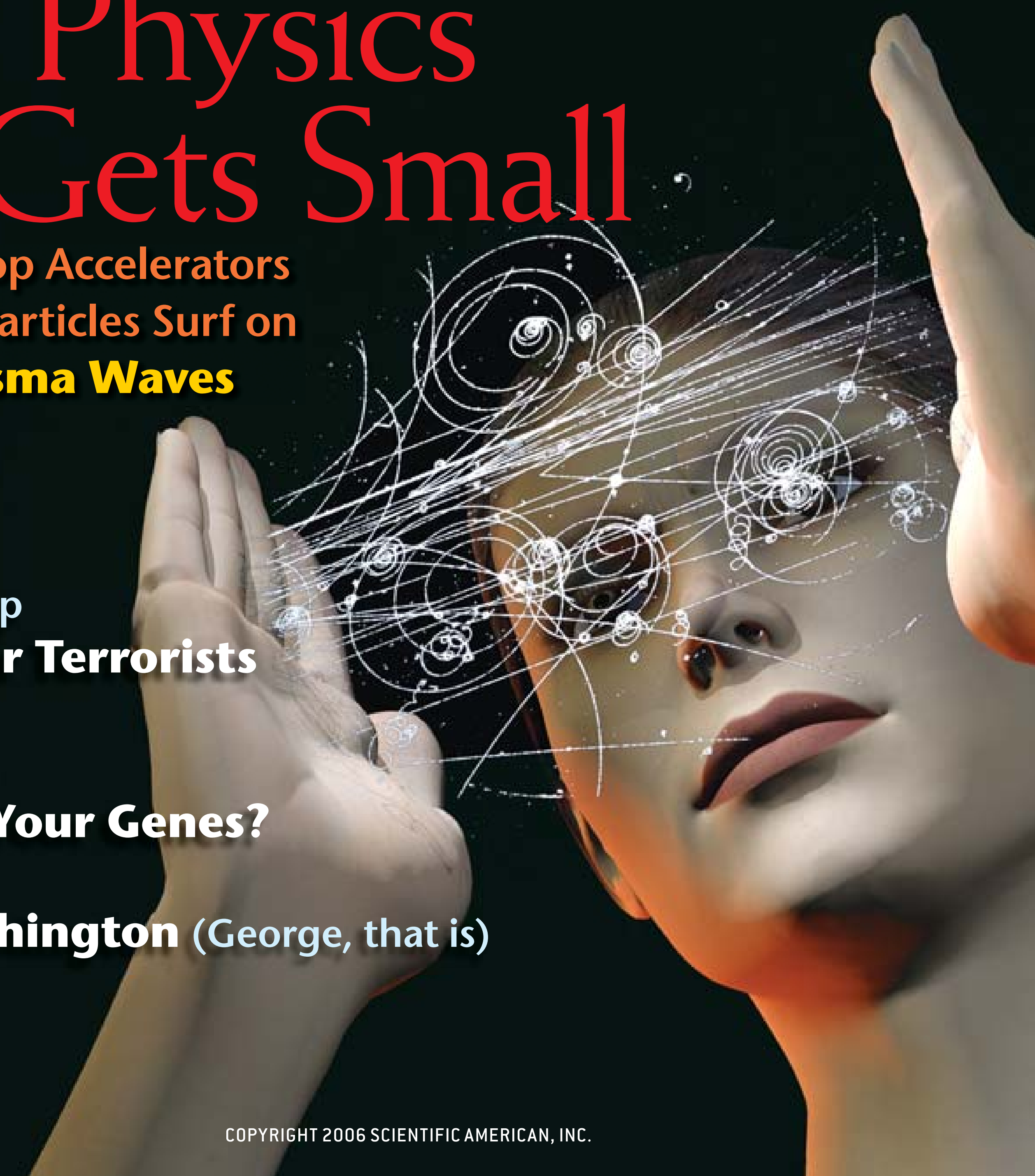
Big Physics Gets Small

Tabletop Accelerators Make Particles Surf on Plasma Waves



How to Stop **Nuclear Terrorists**

Guess Who **Owns Your Genes?**

CSI: Washington (George, that is)

february 2006

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Cover image by Phil Saunders, Space Channel Ltd.; photograph at left by Steve Mirsky.

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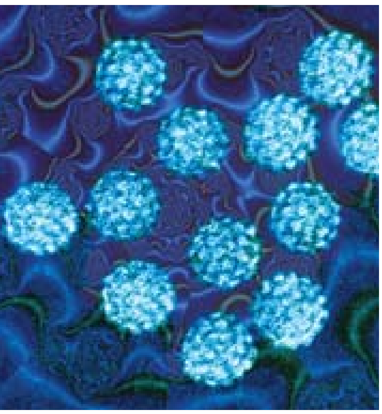
To Banish a Cancer

Medicine usually progresses in incremental steps. One antidepressant or cholesterol-lowering drug follows another with only marginally improved therapeutic benefit. Vaccines are different. Disease prevention through immunization, whether for polio or mumps, has the potential to transform medical practice, sometimes eliminating illness altogether. Smallpox is now (we hope) confined to heavily protected freezers in Russia and at the Centers for Disease Control and Prevention in Atlanta.



CERVICAL CANCER is caused by the human papillomavirus (*above*).

Vaccine developers appear to be on the verge of another remarkable achievement. Two vaccines that are nearing approval by the Food and Drug Administration in the U.S.—one from Merck, the other from GlaxoSmithKline—have demonstrated in clinical trials that they can prevent infection from the two types of the human papillomavirus (HPV) that account for up to 70 percent of cervical cancers. That could make a big dent in a disease that is the second most common malignancy affecting women worldwide and that kills more than half of its victims. In the U.S., in excess of 10,000 women contract invasive cervical cancer annually and nearly 4,000 die of the disease.

The public health community needs to ready itself now for a task as imposing as developing the vaccine. It must convince millions of parents to get their children vaccinated against a sexually transmitted disease. Many youths contract HPV within a few years of their first experience, often in their early teens.

That means that the best time to administer the vaccine is probably between the ages of 10 and 12, when children are less likely to have had sex and when they are scheduled to get boosters for chicken pox, measles and the like. The Merck vaccine also protects against two other types of HPV that cause almost all genital warts, an incentive to get boys immunized, too.

A public health campaign to vaccinate 11-year-olds against STDs will assuredly be a delicate undertaking. A survey that appeared in late November 2005 in the *Journal of Adolescent Health* noted that half of the 513 physicians polled thought that parents would resist immunizing a child against an STD. Physicians also fretted about parents' perceptions of vaccine safety, with 71 percent saying that those concerns could prove a barrier to vaccination.

Worries about antivaccine barnstorming by religious conservatives may be overblown, however. Although some conservatives think that the vaccine will undercut their "abstinence is best" mantra, others have understood that immunization does not exclude a personal decision to refrain from having sex.

Political agendas should be set aside on this one for the sake of public health. The CDC's Advisory Committee on Immunization Practices, which compiles the national list of recommended vaccines, should give Merck's Gardasil and Glaxo's Cervarix its full endorsement. The approval would spur other activity, such as procuring reimbursement from insurers, that would move the vaccine on its way to becoming a routine part of care. And public health officials and drug companies must meet the challenge of mounting a clear and forceful information campaign. The most important message to get across is that this vaccine is a lifesaver and that every child heading into adolescence should get the jab.

THE EDITORS editors@sciam.com

LINDA STANNARD *UCT/Photo Researchers, Inc.*

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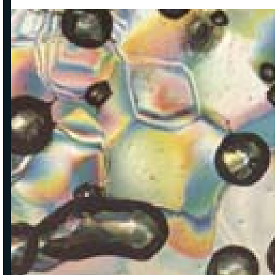

COURTESY OF W. BERNER *University of Bern*

Researchers have recovered a nearly two-mile-long cylinder of ice from eastern Antarctica that contains a record of atmospheric concentrations of carbon dioxide (CO_2) and methane—two potent and ubiquitous greenhouse gases—spanning the last two glacial periods. Analysis of this core shows that current atmospheric concentrations of CO_2 are 27 percent higher than the highest levels found in the past 650,000 years.

Supernovae Back Einstein's "Blunder"

When Albert Einstein was working on his equations for the theory of general relativity, he threw in a cosmological constant to bring the universe into harmonious equilibrium. But subsequent observations by Edwin Hubble proved that the universe was not static. Rather galaxies were flying apart at varying speeds. Einstein abandoned the concept, calling it the biggest blunder of his life's work. New observations from an international team of astronomers seem to show that dark energy is like the cosmological constant, unvarying throughout space and time.

Camera Captures Image of Mysterious Creature in Borneo

A cat-size beast with orange fur and a long, strong tail that may be new to science has been photographed in Indonesia. A camera trap set in the mountains of Kayan Mentarang National Park in Borneo snapped two images of the animal as it trundled through the rain forest.

Ask the Experts

How do electric eels generate a voltage, and why do they not get shocked in the process?
Angel Caputi, head of the department of integrative and computational neuroscience at the Institute for Biological Research "Clemente Estable" in Uruguay, explains.

Letters

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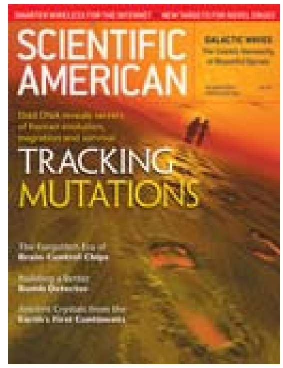


"FASCINATING" APTLY describes the October 2005 issue. Consider Dennis Drayna's "Founder Mutations," which covered genetic changes resulting in conditions such as sickle cell and lactose intolerance that can be used to trace human migrations over thousands of years and also lend support to the Out of Africa theory. And "The Forgotten Era of Brain Chips," in which John Horgan conjured up an odd nostalgia for mid-20th-century brain-chip technology as he looked back on the achievements of brain-stimulation pioneer Jose Delgado and his then controversial vision of a "psychocivilized society." Contemporarily contentious was "Fill This Prescription" [SA Perspectives], about the debate over pharmacists' right to refuse to dispense birth-control prescriptions. Paul S. Braterman of Denton, Tex., wrote, "Imagine what would happen to a checkout staffer who refused to sell cigarettes based on conscience. Why should pharmacists be any different?" But Steve Murphy asked via e-mail, "If a state allows assisted suicide, am I, as a doctor, not allowed to refuse if I believe it to be murder?"

HUMANITY'S GENETIC TRAIL

In "Founder Mutations," Dennis Drayna made an incorrect assumption when he concluded that there was no "successful interbreeding between [*Homo*] *sapiens* and other human groups" during the out-migration from Africa.

Is it possible, or even likely, that the PTC gene mutation occurred much lower on the evolutionary tree, thus making it "available" to *H. sapiens?* Would it not be very selective for the early primates to also have this "bitter-taste" gene? This would distribute the PTC mutation to all humans; thus, no variations would be found—as Drayna reported.

Martin Coyne
Pittsburgh Forensics

Drayna's conclusion that all five nontaster genes are found in Africa and that one has spread globally is offered as strong evidence for the Out of Africa theory. This may be correct, but the argument is extended that the humans from Africa did not interbreed with existing human populations elsewhere, because modern humans have no nontaster genes that developed outside of that continent. If the environmental challenge that the nontaster gene protects against occurred only in Africa, then this gene would provide only a locally specific selective advantage and thus could only originate there. Hence, no nontaster genes would exist outside of Africa, and their absence now would not help answer the interbreeding question.

John Hobson
Wiltshire, England

DRAYNA REPLIES: Coyne and Hobson make thoughtful comments. We now know there are seven different forms of the PTC taste receptor gene, and all but two are limited to sub-Saharan Africa. The best explanation is that older African populations evolved a number of different forms of this receptor to detect a spectrum of toxic compounds in their diets. Evolutionary genetic analysis suggests that two forms—major taster and major nontaster—left Africa perhaps 50,000 to 100,000 years ago and rapidly established themselves at high frequencies worldwide via natural selection. The taster form recognizes at least 50 compounds that contain the chemical group C = N – S, are toxic to the thyroid and taste bitter to PTC tasters. These compounds most likely exist globally, giving rise to selective pressure to maintain this form of the gene worldwide.

The nontaster version is clearly both the mutant form and a recent arrival. We found that all other primates, including the great apes, have only the taster form. Whereas the exact time the nontaster type arose has not been established, the gene is clearly not shared by all humans, because many are *tasters. The simplest explanation is that the nontaster form emerged from Africa at roughly the same time and reached high frequency worldwide by the same kind of selective pressure exerted on the taster form. We have hypothesized that the nontaster variety of this receptor is nonfunctional only for PTC and that it is fully functional for some other unknown toxic bitter substance that might be widely distributed.*

The question about interbreeding between modern and archaic hominids during the Out of Africa dispersal is being addressed by a variety of different studies. Ours provides somewhat different information from the others. All we can say is that the PTC gene today does not carry the variation we would expect if there were a significant archaic contribution to modern populations. The question is far from settled, and one simple answer may not emerge.

THE PLUGGED-IN BRAIN

John Horgan's article, "The Forgotten Era of Brain Chips," provided a much needed historical resurrection of Jose Delgado and his neuroscientific work in the mid-20th century. But the display of "brain chips" in the story would seem inappropriate, because devices of this size were never implanted directly into the brain. [*Editors' note: They were placed on the surface of the skull and attached to electrodes that penetrated the brain.*] It also should have been emphasized that the great accomplishments in brain surgery brought about by modern scanning technology were not available in Delgado's time. Consequently, the ability to properly localize the appropriate deep-brain loci for stimulation or ablation would not have been available and thus would have seriously compromised the use of this technology, particularly in humans.

Robert J. White
Case Western Reserve University
School of Medicine

PRESCRIBING MORALITY

"Fill This Prescription" [SA Perspectives] contains factual errors and false assumptions. You state that when a woman has a prescription filled by a pharmacist, her "health is at the mercy of her pharmacist's conscience." As a physician and a patient, I do not want pharmacists to suppress their consciences. Pharmacists protect patients and aid physicians. We depend on them not only to dispense medication correctly but also to judge interactions with patients' other medical regimens and conditions. They act on knowledge that the physician or patient may not have about the risks from a given medication. They also determine a prescription's legitimacy and enforce it.

PILL STOPPERS: **Who controls birth control?**

The latest medical data indicate that morning-after pills block ovulation when they work. There is no evidence that they stop the implantation of an embryo. Some other points: in nature, human pregnancy begins in the fallopian tube at fertilization; birth control that prevents conception is not synonymous with abortifacients; and the difference between dispensing abortifacients or antivirals is that the former is intended to end the life of a human being, whereas the latter is intended to save it.

Beverly B. Nuckols
Founder, LifeEthics.org
New Braunfels, Tex.

As an OB-GYN for nearly 40 years who has dealt with pain, suffering, and life and death, I have relegated my personal philosophy in favor of the informed direction of those I treat and their families many times. It is not always easy, but that is what health professionals do. I believe any pharmacist not filling a legitimate prescription (or even redirecting a patient to where it can be filled) is acting unprofessionally, if not illegally. Should any court find that failure to fill such a prescription resulted in the birth of an unwanted baby and that the accused pharmacist was responsible for that child's support, the philosophical differences would evaporate instantly.

Harris F. Simmonds
Greenbrae, Calif.

THOSE DOGGONE DETECTORS

"Better Than a Dog," by Gary Stix, intrigued me. I shoot regularly and also use the subway. What will happen when I wear the jacket that I wore to the range yesterday past one of the miraculous explosives detectors so ably described in the article? What about the police and others who legitimately carry weapons? If the detector is set not to reveal certain types of explosives (such as those in smokeless powder), then the bad guys will use those materials for their evil acts.

Finding a solution that allows passage for legitimate weapons bearers while detecting people determined to subvert the system will either make it so unreliable as to be mere "security theater" or raise its cost beyond its benefits.

Charles Shapiro
Avondale Estates, Ga.

ERRATUM In "A Cool Early Earth?" by John W. Valley, the axis labels for the "Ancient Age" graph were mistakenly reversed.

CLARIFICATION In "The Forgotten Era of Brain Chips," by John Horgan, the caption on page 70 should have noted that the photographic sequence is actually a composite from different trials conducted on the same day. The frames were selected when the successful results were first published, and no full set of images from any single trial remains. Also, to clarify an ambiguity: the bull turned to Jose Delgado's left.

DAMIEN LOVEGROVE *Photo Researchers, Inc.*

50, 100 & 150 Years Ago

FROM SCIENTIFIC AMERICAN

Scientific Freedom ▪ Dead Suns ▪ Heating with Mummy

FEBRUARY 1956

EMANCIPATING SCIENCE—"Racial segregation was a major theme at the annual meeting of the American Association for the Advancement of Science in Atlanta. Four affiliates of the A.A.A.S. had refused to go to Atlanta. Some prominent Negro scientists also boycotted the meeting. Negroes who attended were unrestricted at official functions of the convention but were barred from white hotels and restaurants. A submitted resolution said in part: 'It is necessary and desirable that all members may freely meet for scientific discussions, the exchange of ideas and the diffusion of established knowledge.... These objectives cannot be fulfilled if free association of the members is hindered by unnatural barriers.'"

THE NEW RETIREE—"The notion that retirement makes a person discontented is contradicted by an interdepartmental study now in progress at Cornell University. Three fourths of about 700 recently retired men indicated that they are satisfied with their new way of life and are generally in good health. Generally speaking, those who are content with retirement were financially secure and had made plans for the future."

FEBRUARY 1906

CRETACEOUS CRITTERS—"The illustration depicts two great reptiles struggling for supremacy. These are Dryptosaurs, which, while much smaller than Tyrannosaurus and of an earlier period, were in all probability exceedingly like the latter in habits and general appearance. The restoration is believed to be correct, though it is not thought that the animals ever exhibited such agility as shown, for none of the thousands of footprints of Dryptosaurus is such as to warrant a conception of this character. The illustrations are after restorations by Charles R. Knight which so excellently supplement the exhibition of paleontological specimens at the American Museum of Natural History of New York City."

DYNAMIC DINOSAURS, after Charles R. Knight, 1906

EXPANDING UNIVERSE—"Photographs of the entire celestial vault reveal about one hundred million suns. These may be ignored. It is known to mathematicians that there is matter enough in existence to make thirty-two billion suns equally as massive as our own. Proof is had from velocities of rapid suns. A minute fraction appears in the form of visible suns. But what of the rest? Is it in dead suns, planets, and moons? Is it possible that billions of exhausted suns are now wandering in waste places of space? And are they all surrounded by dead planets, still in revolution, counting off lifeless and useless years?"

HAPPY VALENTINE'S—"Few people realize what a large industry has grown out of the custom of giving valentines on the 14th of February each year. The valentine idea seems to have originated in England, and is now practiced by English-speaking people the world over. Germany, although it does not recognize the day, supplies many of the cards and novelties used in the United States. Of late years America has taken the lead in the valentine industry. Now we not only supply our own market, but export large quantities of valentines to all parts of the world."

FEBRUARY 1856

FUEL PRICES—"The fuel required to cook a dinner in Paris costs nearly as much as the dinner itself. Fuel is very scarce, and the American is surprised to find shops all over the city, fitted up with shelves like those in shoe stores, upon which is stored wood, split in pieces about the size of a man's finger, and done up in bundles, like asparagus. Larger sticks are bundled up in the same way, and sell at a frightful price. Hard coal being nearly as expensive as wood, can be bought in the smallest quantity at any of these fuel shops."

FATE OF THE MUMMIES—"The mummies of Egypt are sometimes quarried by the Arabs for fuel, and, whether those of the Pharaohs, their wives, their priests, or their slaves, are split open and chopped up with the same indifference as so many pine logs. The gums and balsams used in embalming them have made them a good substitute for bituminous coal; and thus the very means employed to preserve them have become the active agents of their dissipation."

news SCAN

EARTH SCIENCE

Polar Satellite Freeze

DELAYS MIGHT UNDERMINE CLIMATE STUDIES AND FORECASTS **BY CHARLES Q. CHOI**

BEHIND SCHEDULE: An artist's conception of an orbiter of the National Polar-orbiting Operational Environmental Satellite System (NPOESS). The program may not start launches until April 2009.

COURTESY OF NATIONAL POLAR-ORBITING OPERATIONAL ENVIRONMENTAL SATELLITE SYSTEM (http://npoess.noaa.gov)

The long-range weather forecasts that warned of where Hurricane Katrina would strike depended on data from polar satellites. They capture not only details over the Arctic and Antarctic but also virtually every point on the planet's surface as the world turns under them. Now the replacements for the aging U.S. military and civilian fleet are in jeopardy. The program is as much as $3 billion over budget, and the launch of the first replacement satellite is as many as three years behind schedule.

Today two agencies each maintain two polar satellites at a time: the National Oceanic and Atmospheric Administration and the U.S. Department of Defense. In 1994 the U.S. decided to create the National Polar-orbiting Operational Environmental Satellite System to serve the combined needs of NOAA and the DOD. The joint program's six orbiters would pack in 14 instruments, roughly twice as many as either military or civilian polar orbiters, and save $1.8 billion.

After the U.S. awarded the satellite contract to Northrop-Grumman in 2002, a test satellite with four sensors was supposed to fly this May, and the first fully functioning replacement was set to roll out in June 2008. Now the launch of the test orbiter (overseen by NASA) is delayed until April 2009 and the first replacement is pushed to 2012, NOAA and Defense Department officials testified before the House of Representatives science committee in November. "It is now clear that almost from the outset decisions were made with too little analysis of the technical challenges involved," said committee chairman Representative Sherwood Boehlert of New York at the hearing.

Northrop-Grumman explained that most of the delays and cost growth resulted from problems with the orbiters' sensors. One in particular concerned an infrared camera dubbed VIIRS, which is supposed to collect images of clouds and probe sea-surface temperatures. Northrop-Grumman now says that it assumed VIIRS development would be simpler than it turned out to be because aspects of VIIRS were based on existing instruments.

Both the government and contractors failed to recognize problems in time to fix them, stated David Powner of the Government Accountability Office at the hearing. Powner also noted that the satellite program's executive leadership issued few major decisions, often opting instead to conduct further analysis and review.

To get the program back on track, NOAA, the DOD and NASA hired a new joint program manager. Moreover, Raytheon, the subcontractor building VIIRS, replaced the entire team working on the instrument, and Northrup-Grumman has increased oversight of its subcontractors. To save costs and time, NOAA administrator Conrad C. Lautenbacher said the program might eliminate some sensors from the orbiters. Still, an independent review conducted by the Aerospace Corporation suggests any changes will still leave it at least $1 billion over budget. The House science committee also worries that the joint agency nature of the program hampers problem solving.

Workarounds are possible, if not ideal. The military satellites can probably survive well beyond 2012, although they do not provide all the data NOAA needs for its weather-forecasting models. NASA research satellites or long-duration high-altitude flights might also help. Lautenbacher noted that engineers could bolster the test orbiter—it can already obtain 93 percent of the data that fully functioning satellites can—and could keep existing NOAA polar satellites flying past their average four-year useful life span. European satellites might be an option—if they are available and produce data in a format compatible with U.S. weather-forecasting models.

A revised plan for the program should fall into place this spring. In the meantime, NOAA and the DOD will launch the last of their original polar satellites in December 2007 and October 2011, respectively. If NOAA's fails, as roughly one out of every 10 do during or right after launch, U.S. civilian polar orbiter coverage might suffer a gap of four years or more. (That satellite might be especially prone to failure because the contractor, Lockheed Martin, accidentally dropped it, causing significant damage.)

A gap could be serious, explains Richard A. Anthes, president of the University Corporation for Atmospheric Research in Boulder, Colo. It could, he remarks, "make the difference on whether a forecast of where a hurricane makes landfall has an error of a few tens of miles or a few hundred miles."

Charles Q. Choi is a frequent contributor.

NEED TO KNOW: POLE POSITION

Instruments planned to be onboard the National Polar-orbiting Operational Environmental Satellite System orbiters include:

- Microwave imagers to clock ocean winds, help predict El Niño and aid aircraft carriers
- Space-weather sensors to detect disturbances from solar flares that can disrupt communications and power systems
- Aerosol detectors to predict aviation hazards such as volcanic ash and help the military spot targets
- Ocean-color sensors to track fish and pollution and assist the navy in sweeping for mines
- Search-and-rescue tracker to locate aviators, mariners and others in distress

HOMINIDS

Food for Thought

GIANT HOMINID TEETH NOT FOR CRUNCHING NUTS, BUT SHELLFISH BY KATE WONG

For the first million years of their existence, the early members of our genus, *Homo*, shared the African landscape with another group of hominids, the robust australopithecines. Although the two groups were closely related, there were striking differences between them. Perhaps most notably, the robusts had giant molars, thick tooth enamel and a bony crest atop the skull that anchored huge chewing muscles. Paleoanthropologists have long believed that the robusts used their elaborate headgear to process tough plant foods. But the results of a new study suggest otherwise.

Received ecological wisdom holds that two closely related species cannot live side by side unless they differ significantly in the way they use local resources. To explain how early *Homo* coexisted with the robusts for so long—and under the difficult circumstances of a global drying trend that replaced food-rich forests with grasslands—experts concluded that whereas *Homo* developed a large brain and tool-making capabilities that enabled it to pursue a diet rich in meat, the robust australopithecines became dedicated vegetarians, evolving the anatomical equivalent of a Cuisinart to grind up nuts, fruits,

NARROW SAMPLE?

To date, fossils of robust australopithecines have all turned up in or near what were once wetland environments, which is consistent with the hypothesis that they specialized in eating freshwater crabs and mollusks. This may be an artifact of preservation, however, because these same environments offer the most favorable conditions for fossilization. The discovery of robusts far away from wetlands would weaken or disprove that hypothesis.

seeds or tubers, or some combination thereof.

But in recent years the various vegetarian scenarios have come under fire, in large part because of findings from studies of carbon isotopes. These isotopes derive from the food an animal eats and become incorporated into its tissues over time. In the case of the robusts, the ratio of carbon 13 to carbon 12 in their teeth is higher than would be expected of animals that ate mostly fruit and nuts but lower than that of creatures that subsisted on grass seeds. This discrepancy prompted experts to wonder whether the robusts were instead omnivores. The problem is, their anatomy is not what one would expect to see in an equal-opportunity eater.

At the annual meeting of the Society of Vertebrate Paleontology in Mesa, Ariz., last fall, graduate student Alan B. Shabel of the University of California, Berkeley, offered up a possible solution to the riddle of the robusts. He proposed that they were built for eating not tough plant stuffs but hard-shelled invertebrates. Shabel noted that although eastern and southern Africa, where the vast majority of the continent's hominid fossils have turned up, were indeed undergoing desiccation at the time of early *Homo* and the robusts, wetlands still abounded, as they do today. And like modern wetlands, these ancient lakes, rivers and marshes would have been rich in crabs and mollusks, such as giant land snails.

Looking at the contemporary African animals that specialize in eating these prey—namely, the Cape clawless otter and the marsh mongoose—Shabel found that they have the same suite of peculiar skull features seen in the robusts. They use their powerful chewing apparatus to crunch through the shells. If, as current evidence indicates, the robusts lived in wetland areas, perhaps they, too, evolved to exploit these armored invertebrates.

DAVID L. BRILL

HUGE MOLARS and chewing muscles enabled robust australopithecines to make mincemeat of shellfish, a new theory posits.

To test that hypothesis, he performed carbon isotope analyses on the otter and the mongoose and their quarry. Their chemical signatures were comparable to those known for the robusts. According to Shabel, that makes his theory of what the robusts were dining on the only one that is consistent with all the available data.

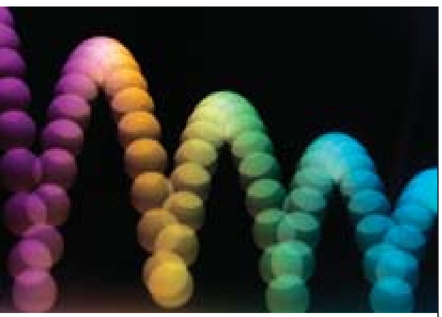
Other researchers find the idea hard to swallow. To be sure, the robusts had the occasional crab cocktail, surmises paleoanthropologist Donald C. Johanson of Arizona State University. But he doubts that they were specialized to do so: “It is much more likely that [they] subsisted predominantly on a low-quality vegetarian diet, which required significant masticatory preparation.”

Shabel, meanwhile, is conducting a much more extensive isotope analysis, which will include more than 1,000 samples of bone, hair and enamel from all the small- and medium-size carnivores found in southern Africa. This will reveal whether the chemical signatures in the tissues of shellfish eaters are indeed unique. His results will no doubt give paleoanthropologists plenty to chew on.

MATERIALS

Bouncy Proteins

SYNTHETIC VERSION OF INSECT SUPER-RUBBER SPRINGS FORTH BY STEVEN ASHLEY



BOUNCE PASS: A natural rebounder called resilin would easily surpass the best playground balls.

Playground veterans appreciate the marvel that is the SuperBall, the hard plastic sphere that rebounds almost completely when dropped and then just seems to keep on bouncing. Scientists have recently synthesized nature’s version of the SuperBall. Called resilin, the ultraenergy-efficient elastic protein enables fleas to make their leaps, flies to flap their wings and cicadas to sing their songs. An artificial version might find use in biomedical or industrial applications—perhaps as new stents, heart valves, spinal-disk implants, nanohinges, even running-shoe soles.

First identified some 40 years ago, resilin has long been a target of biomimetic engineers—researchers who work to imitate or copy biological systems. One similar biomaterial that has achieved some practical success is elastin, a protein that allows tissues such as blood vessels to resume their shape after being flexed.

Elastin and resilin share a common structural arrangement that accounts for their rubbery properties—each contains randomly coiled amino acid chains tied together at intervals with molecular cross-links, explains Julian Vincent, a professor of biomimetics at the University of Bath in England. When resilin is swollen with water, its coils can rotate freely, which allows the proteins to unwind as they elongate. Both substances stretch substantially without breaking—elastin by 100 percent, resilin by at least 300 percent.

Soon after scientists identified the gene that codes for resilin in the fruit fly genome in 2001, Christopher M. Elvin of CSIRO Livestock Industries near Brisbane, Australia, started planning to make it himself. As he and his team reported in the October 13, 2005, *Nature,* they began by transferring the functional part of the resilin gene into *Escherichia coli* bacteria. The researchers then grew batches of the microbial factories that expressed the fruit-fly gene and produced the raw protein as a runny solution called pro-resilin.

Converting pro-resilin into a rubbery solid required forming molecular cross-links between the spiral peptide strands. After trying several techniques, Elvin and his colleagues finally succeeded by briefly exposing the pro-resilin to light in the presence of a metal catalyst and an oxidant. This measure initiated a photochemical reaction that generated the needed cross-links.

The solid recombinant resilin features properties matching those of the natural version, Elvin says. The group is now working to better understand the material’s basic function so it can synthesize novel polymers that incorporate as building blocks the protein sequence responsible for elasticity.

NEED TO KNOW: ON THE REBOUND

One measure of a material’s “springiness,” or resilience, is the degree to which it recovers stored energy as motion when it is deformed and how much it loses as useless heat. Whereas the resilience of the basic stuff of SuperBalls—polybutadiene plastic—is around 80 percent, for the insect protein resilin it is 97 percent or more. Resilin, in addition, retains its ability to bounce back over hundreds of millions of mechanical cycles. Well-used SuperBalls, in contrast, often break apart into chunks.

ADAM HART-DAVIS *Photo Researchers, Inc.*

Several problems need solving before practical applications emerge, however. Natural resilin is extremely stretchy, but it is not very stiff. Nature handles this drawback by weaving it with tough chitin; the same kind of approach may be needed to bolster the man-made version. In addition, because the protein is biodegradable, it will most likely require modification if it is to be used in wet environments, such as in the body. Finally, alternatives to water will be required to maintain resilin's elasticity in dry conditions. "Although the potential seems enormous, now we have to make it work," Elvin emphasizes. "And that lies perhaps 10 years down the track." Should that occur, the next big playground fad might just be "UltraBalls."

SOCIETY

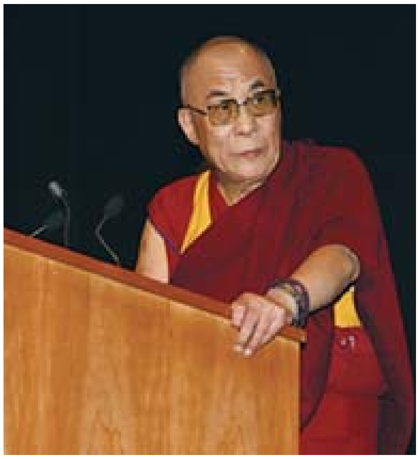
Talking Up Enlightenment

NEUROSCIENTISTS HEAR—AND APPLAUD—THE DALAI LAMA BY CHRISTINA REED

Many years ago a curious boy looked through a telescope and, on seeing the shadows in the craters of the moon, realized that he had to make a choice. His religion taught him to respect the moon as a generator of light, but science taught him that the moon reflected the sun's rays. The subtle clarification offered by science ultimately trumped the Buddhist interpretation for Tenzin Gyatso, the current Dalai Lama.

Today when this political and religious leader is faced with conflicting explanations of life's mysteries, the Dalai Lama still favors scientific evidence over classical Buddhist concepts. At a time when Americans are battling state by state for religion-free science education, he urges people to take a path of peace between the perspectives. An estimated 14,000 people attended his lecture on November 12, 2005, at a meeting of the Society for Neuroscience in Washington, D.C., with most of them watching from overflow rooms where the talk was broadcast on large screens. Dressed in gold and crimson robes, he suggested a healthy dose of skepticism toward religious pronouncements. Although science can overturn spiritual teachings, people can benefit from scientific understanding without losing faith, he reasoned.

But the Dalai Lama also emphasized that religion can help science, not just hinder it. In particular, he urged neuroscientists not to discount the role of Buddhist traditions on the brain, specifically meditation. "Try to find reality with an open mind," he said, referring both to investigations in science as well as to studies in Buddhist thought. "Without investigation we can't see reality."



DALAI LAMA, at a Society for Neuroscience meeting last November, said that in cases of conflicting explanations, he would favor strong scientific evidence over religion.

The neuroscientists in the auditorium responded with approval, especially those who have examined the effects of meditation. One was Bruce F. O'Hara of the University of Kentucky, who has found that meditation improves the performance of sleep-deprived individuals about as much as drinking a cup of coffee does. O'Hara applauded the religious leader's support of science, "especially given the issues with evolution and the [fundamentalist] Christian reluctance to accept evolution because it threatens their beliefs." Olivia Carter of Harvard University found it fascinating to hear about the Dalai Lama's personal interest in neuroscience and the importance he places on the scientific method of inquiry. "It should not matter that the observations associated with meditation arise through introspection or contemplation, as long as the observations can be used to generate objective testable predictions," she says. Carter's own work in the field examines meditation's effect on perception.

Sara W. Lazar of Harvard Medical School remarks that not all scientists are equally as open to testing Buddhist meditation practices. "I have encountered mainstream scientists who do not meditate who are very curious and open, and those who are still unwilling to even consider the possibility that meditation might have some positive effects." Lazar has found that meditation may help prevent the rate of cortical thinning with age. Brain scans show that as people get older, the white matter typically degenerates. This material envelops the neurons and helps them work more efficiently. Lazar discovered that older meditators had active cortical regions that were comparable to those of younger nonmeditators.

But such a discovery should not have been too surprising, according to neuroscientist Michael Merzenich of the University of California, San Francisco. The brain typically responds to repetitive use by thickening the cortex in the relevant area—for example, people who play the piano have more cortex associated with that skill. Moreover, recent studies indicate that "plastic changes driven by mental exercises in many respects parallel those driven by actual exercise," Merzenich says.

Still, he finds the idea of science studying the influence of faith on the brain intriguing. Imaging work has shown that an area in the frontal cortex is activated in response to how strongly someone believes an answer to be correct. Merzenich adds that "this activation affirms the brain's decision that one's conclusion is correct, whether it is or not." Such findings reinforce why the Dalai Lama places so much importance on maintaining an open mind.

Christina Reed is a science writer based in Washington, D.C.

MISSING PROTEST

Before the November 2005 meeting of the Society for Neuroscience, hundreds of scientists signed a petition against having the Dalai Lama speak about the neuroscience of meditation in the first of a new lecture series entitled "Dialogues between Neuroscience and Society." The mixing of science and religion was one concern, and politics may have been another—many who opposed it were originally from China. But on the day of the speech, the only visible protest came from a postdoctorate Chinese national with residence status in the U.S., who quietly sat holding a scrawled statement saying that the Dalai Lama was not qualified to speak at the meeting.

Next year architect Frank Gehry will give the 2006 "Dialogues" lecture. His participation is not expected to draw such criticism.

AWARDS

Winner Takes All

ARE TECH PRIZES THE BEST WAY TO THE CUTTING EDGE? BY PATRICK DI JUSTO

Economists call them *ex ante* rewards. They are the technology prizes designed to spur innovation, challenging entrepreneurs to do something that outstrips the state-of-the-art in return for a sizable payoff. They have yielded a wealth of advances, including precision timepieces, unpickable locks and private suborbital joyrides. Awards up for grabs today include those from J. Craig Venter's science foundation, which may offer as much as $10 million for anyone who can develop automated technology that can sequence a human genome for $1,000, and NASA, which is offering $250,000 for a machine that can extract oxygen from lunar soil. Is basic research being prized out of the market?

"Anytime you do research and development, there's a cost associated with it," says Ian Murphy, director of media relations for the X Prize Foundation, which rewarded the first private manned suborbital flight. "What a prize does is to create a sense of competition that allows you to leverage your money. The Ansari X Prize was a $10-million prize, but a little over $60 million of research was spent by everybody. And when you're done, you only have to pay the winner."

But there's no such thing as a free lunch, according to Douglas Holtz-Eakin, director of the Congressional Budget Office. "Prize competitions do not change the underlying factors that determine risks and rewards," he warned in a 2004 appearance before the House Subcommittee on Space and Aeronautics. "Innovators and researchers must be paid for what they do. Inducement prizes have to be very large if the objectives sought are risky and expensive."

From an entrepreneur's point of view, how the prize is paid out matters as much as the size. One drawback to many technology prizes, such as the Defense Advanced Research Projects Agency's Grand Challenge to develop a robotic ground vehicle, is that they often lack a tiered award structure, opting instead for a single large pot for the winner. In an early example, the $25,000 New York–to-Paris Orteig Prize, won by Charles Lindbergh in 1927, had nine entrants, seven of whom spent more than the amount of the prize money in their attempt. When those teams lost, they lost big.

Even the people at the X Prize Foundation realize the drawbacks of a winner-take-all approach. "Toward the end we were thinking, 'Boy, we wish we had a second- and third-place prize,'" Murphy concedes. In a subsequent study for NASA's Centennial Challenges, the foundation determined that a multitiered prize structure—with purses of $150 million, $75 million and $50 million—would provide the right incentive to develop a human orbital vehicle. "This allows the companies that are really, really close to continue to work, to continue to find investors," Murphy explains. "You're also encouraging multiple firms to stay in the market, hence driving down that competitive price. That's what it's all about."

Patrick Di Justo is based in New York City.

PRIZE of $10 million went to SpaceShipOne.

SCALED COMPOSITES, LLC

RAISING STANDARDS

All the prize money in the world will not advance an industry if the challenge does not push the envelope. For all its new design and materials, SpaceShipOne, the winner of the Ansari X Prize, essentially replicated the flight of the X-15, an experimental plane developed nearly 50 years ago, says Randa Milliron, co-founder of Interorbital Systems, an unsuccessful Ansari X Prize competitor. She contends that the prize did not set the bar high enough. "We should be going into Earth orbit or even lunar orbit," she insists. "That's what the industry needs." Her company is focusing on raising the money to create a privately developed five-person orbital spacecraft by 2008. "You want to give us a challenge?" she asks. "Give us a challenge that actually takes us somewhere."

ENERGY

Pinching Out Sulfur

REFINING WAYS TO TURN HEAVY OIL INTO SWEET CRUDE BY JR MINKEL

Removing sulfur is a stinky proposition for oil refineries. The U.S. and Europe are tightening limits on the sulfur content of gasoline at the same time the crude oil coming out of the ground is becoming increasingly "sour," or sulfurous. Desulfurization technology "has pretty much been wrung out," says Thomas Wellborn, principal consultant of Denver-based Hydrocarbon Exploration and Development. "We need new, innovative technologies." A few young companies with unconventional methods may soon answer that call.

Refineries separate crude oil by boiling point, which is related to density. Most desirable are the lighter (less dense) fractions, which include gasoline and diesel. Heavier fractions contain more sulfur, and too much renders the petroleum useless. Decades ago oil refineries adopted a process called hydrodesulfurization (HDS) to strip sulfur atoms from oil molecules. Sulfurous fractions are mixed with hydrogen and a cobalt-molybdenum catalyst, yielding hydrogen sulfide. Providing hydrogen for the process is expensive, and as oils get more sour, higher pressures and more stable catalysts are needed to break the sulfur bonds. Sourer oils also tend to be heavier, which requires further refining and brings along nitrogen and heavy metals, which foul the catalyst.

Alternative technologies floated in recent years include sulfur-eating bacteria and sulfur-oxidizing reagents, and some experts see room for better-designed catalysts, too. These methods tend to operate on the distilled fractions, but pretreatment of the crude oil itself may be an attractive option. "The better the selectivity upstream, the less need for energy- and capital-intensive separation processing downstream," says Charles Russomanno, a technology transfer manager at the U.S. Department of Energy.

One pretreatment option may be ultrasound. When blasted with ultrasonic waves, liquids can undergo a process called acoustic cavitation, in which bubbles form and violently implode. SulphCo is developing small, modular ultrasound desulfurization units based on this effect. The company, located in Sparks, Nev., claims its process can both snap loose sulfur atoms and lighten the crude, resulting in 30 to 50 percent less sulfur and about one third more diesel and kerosene. "If SulphCo's process works, it's an elegant solution to part of our problem," Wellborn says.

Refineries would have to integrate

OIL SANDS contain sulfur that must be removed. Sweetening such crude oil could be achieved more economically with a sulfur-stripping technique from SulphCo, in which an ultrasonic probe generates bubbles that implode in a billionth of a second (*right*). The process, called acoustic cavitation, creates transient temperatures of about 5,000 degrees Celsius and pressures of about 1,000 atmospheres.

SUNCOR ENERGY, INC. (*top*); SULPHCO, INC. (*bottom*)

such units into their process, combining pretreatment and post-treatment. "It gets into pretty complex equations to balance the two together," says Abe Albert, a refining specialist for Hart Downstream Energy Consulting in St. Louis. On the plus side, SulphCo president Peter Gunnerman says, the treatment would make downstream desulfurization more efficient, and the capital investment would be only 5 percent that of HDS. SulphCo completed a small demonstration unit in South Korea last September.

Another technique is designed to remove all the sulfur from very heavy oils in one shot. Trans Ionics, based in the Woodlands, Tex., is focusing on so-called tar sand, or bitumen, an especially heavy and sour oil of which the Western Hemisphere holds 65 percent of the world's reserves, primarily in Canada and Venezuela. To deal with such heavy oils, refineries would typically thermally "crack" the oil (that is, cook it) and then treat the liquid products. Trans Ionics intends to extract sulfur with elemental sodium, which would then be recycled in a novel sodium sulfide battery. Funded by DOE grants, Trans Ionics has filed for patents on various components, including a novel thin-film electrolyte, says company president Robert Schucker, who expects commercialization by 2012.

The world's refineries were originally tailored to a much less stringently regulated world, notes Douglas Rundell, a BP refining technology project leader in Naperville, Ill. The challenge to the myriad proposals for new methods is to prove they can reliably augment that infrastructure. Refiners are open to a well-argued case, Rundell says: "If somebody comes along and shows that process 'x' works and the economics are compelling, people will go with it."

JR Minkel is a frequent contributor.

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DATA POINTS: GOOGLING IT

Web searching is catching up to e-mail as the primary activity for U.S. Internet surfers, according to a recent Pew Internet & American Life tracking survey.

Number of Americans who use the Internet every day: 94 million

Number who read or wrote e-mail on an average day in:

June 2004: 57 million

September 2005: 74 million

Percent increase: 29.8

Number who used search engines in:

June 2004: 38 million

September 2005: 59 million

Percent increase: 55.3

Percent of Internet users each day who:

Wrote/read e-mail: 77

Used a search engine: 63

Read news: 46

Did job-related research: 29

Instant-messaged: 18

Banked: 18

Participated in a chat room: 8

Booked travel: 5

Read blogs: 3

Participated in an auction: 3

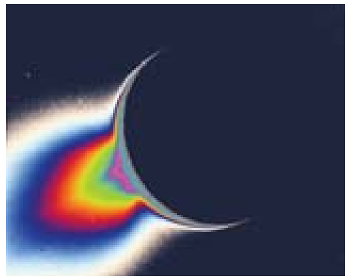
SOURCE: Pew Internet & American Life Project, search engine use report, November 2005

PLANETS

Tiger, Tiger, Burning Bright

Saturn's satellite Enceladus is shaping up as the star of the Cassini mission. Observations last year suggested that plumes of water vapor and dust tower above the moon's southern hemisphere, feeding a tenuous atmosphere and producing one of Saturn's rings. Now Cassini's camera has caught the plumes in the act. They appear to vent out of "tiger stripes"—parallel cracks that glow conspicuously in infrared images, a sign of escaping heat. Enceladus thus becomes the fourth body in the solar system (after Earth, Jupiter's moon Io and Neptune's moon Triton) with known active volcanism. What drives its geologic activity and frames its fearful north-south asymmetry, no one dares to say. The satellite is so small, just 500 kilometers across, that heat from its distant deeps should have leaked out long ago, and tidal forces do not seem up to the task. Additional details may have to wait for the next Cassini close flyby, in March 2008.

—George Musser



PLUME emerges from Enceladus in this image colored to enhance the contours.

PALEONTOLOGY

Greener Cretaceous Pastures

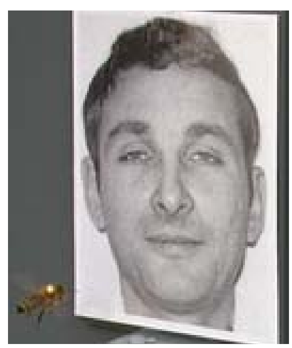
Paleontologists had thought that grass evolved well after dinosaurs died out 65 million years ago. Now Swedish researchers studying "coprolites"—fossilized dino doo—have discovered tiny silica crystals characteristic of relatively evolved grasses. These bits of undigested plant matter, or phytoliths, come from a site containing bones of titanosaurs, long-necked plant eaters that lived near the end of the dinosaurs' reign. The five different grass phytoliths date back 65 million to 67 million years, meaning grass first sprouted up to 100 million years ago, the researchers guess. They speculate the grasses were tall, herbaceous and, based on the coprolites' other contents, just a small part of the dino's diet. Graze the November 18, 2005, *Science* to digest the findings.

—JR Minkel

ENTOMOLOGY

Sight for Bee Eyes

Honeybees can learn to recognize human faces. Adrian G. Dyer of the University of Cambridge and his colleagues trained the bees by getting the insects to associate black-and-white mug shots with a sweet reward (a sucrose drink) or with a bitter punishment (a quinine solution). During tests, which offered no reward or punishment, smarter bees did not bumble the task. They hovered two to three inches from the photographs before correctly landing near the "reward face" 80 to 90 percent of the time. They also performed well when novel and stick-figure faces were part of the selection. The results demonstrate that face recognition, which might seem to be a sophisticated neural ability, does not need much brainpower—bees have less than 0.01 percent the neurons that humans do. Generating the buzz is the December 15, 2005, *Journal of Experimental Biology*. *—Philip Yam*



THAT'S HIM: Honeybee trained to recognize faces hovers to inspect an image.

NASA/JPL/SPACE SCIENCE INSTITUTE (*top*); COURTESY OF ADRIAN G. DYER, REPRINTED WITH PERMISSION FROM *JOURNAL OF EXPERIMENTAL BIOLOGY*, VOL. 208; DECEMBER 15, 2005 (*bottom*); ILLUSTRATION BY MATT COLLINS

PREVENTION

Fiber Irregularities

HIGH INTAKE of fiber may not lower the risk of colorectal cancer.

Will the real relation between dietary fiber and colorectal cancer please stand up? Depending on the study design and type of fiber investigated, reports find that fiber protects you from colorectal cancer, does nothing, or even bumps up your risk. The latest big study, published in the December 14, 2005, *Journal of the American Medical Association,* pooled the results from 13 prospective studies, which together tracked some 725,000 people for up to 20 years. Although they could not control for confounding dietary factors or solubility of fiber, the authors found that those eating the least fiber (less than 10 grams a day) were at increased risk of colorectal cancer. But high intake of fiber did nothing to reduce risk. The results also suggested that fiber from cereals and whole grains, but not from fruits and vegetables, confers a somewhat lower risk of rectal cancer. *—JR Minkel*

BEHAVIOR

The Devil You Know

Experimental economists know that people prefer games involving known risks, not ambiguous ones. Now they have a better idea why. Researchers from the California Institute of Technology had volunteers play two games while undergoing brain-imaging scans. In one game, subjects could take a small sum of money or potentially win a larger sum by guessing the color of a card drawn from a deck they knew was split evenly between two colors. The second game was identical except that subjects did not know the proportions of the cards. This more ambiguous game activated the amygdala and orbitofrontal cortex, brain areas associated with emotion processing, whereas the game of known risk did not. The result lends credence to a model in which people caution themselves to avoid the worst possible outcome, as opposed to coolly identifying the best strategy, according to a commentary in the December 9, 2005, *Science.* *—JR Minkel*

PHYSICS

Catch as Quantum Can

In a key step toward quantum computing and communication, two groups have used clusters of atoms to catch and release single photons, and a third has managed to entangle two such clusters. Many quantum-information schemes depend on transmitting quantum bits, or qubits, as photon states. Qubits sent down optical fibers would require periodic purification, which means storing and releasing photons. Teams from Harvard University and the Georgia Institute of Technology independently accomplished this feat. They generated single photons from a coherent quantum ensemble of rubidium atoms and sent them into a second ensemble, which could be rendered opaque by a laser pulse to catch or store the photon and transparent by another pulse to release it, all without degrading the photon's quantum abilities. The third team, led by California Institute of Technology researchers, entangled two ensembles—creating a quantum link between them—across a room. Such entanglement is another requirement for propagating a signal. Check the December 8, 2005, *Nature* for details. *—JR Minkel*

STOCKFOOD

BRIEF POINTS

- **Transgenic peas set off an immune reaction in mice, even though the new gene came from a nonallergenic bean. The cause: a subtly different array of sugar molecules on the gene's protein. The finding, which abruptly ended a field trial, indicates that modified crops could create unanticipated allergy risks unless they are evaluated case by case.**

  Journal of Agricultural and Food Chemistry, November 16, 2005

- **Salt cravings may depend on birth weight: smaller babies preferred saltier water than heavier infants did, a fondness that persisted into preschool.**

  European Journal of Clinical Nutrition online, November 23, 2005

- **Ground-penetrating radar on the Mars Express orbiter has revealed what appears to be thick subsurface water ice at the Martian north pole and at a buried impact crater.**

  Science online, November 30, 2005

- **Relieved of the glacial weight from the last ice age, northeastern North America is slowly springing up and, researchers now find, moving south, by about a millimeter a year.**

  Nature, December 15, 2005

BY THE NUMBERS

Sizing Up

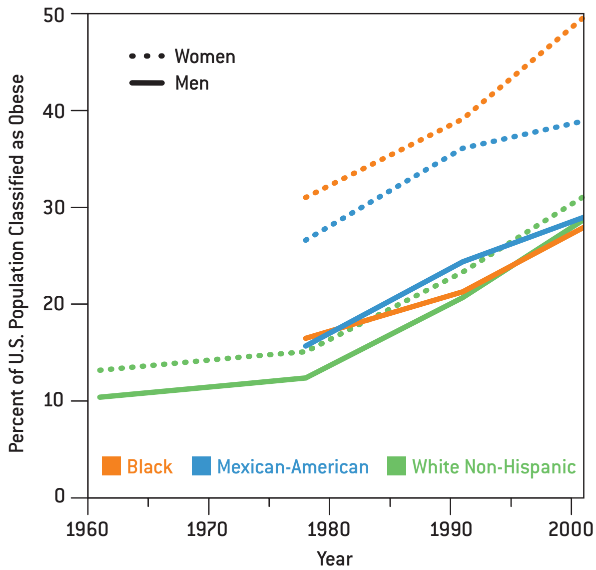
ROOTS OF OBESITY EPIDEMIC LIE IN THE MID-20TH CENTURY BY RODGER DOYLE

Beginning in the 1980s, the average weight of Americans began to soar, and by 2002, 31 percent were classified as obese. Although the reasons for this epidemic remain controversial, researchers have implicated at least four developments: The first is the decrease in energy expenditure throughout the 20th century, following the introduction of automobiles and the replacement of high-energy blue-collar work by low-energy office occupations. The second is the growing affluence of Americans, who could now afford more and better food. The third is the technological transformation of the food industry in the past 30 years that has made available cheap, convenient, high-calorie and tasty foods. The last is the decline through much of the 20th century in extended breast-feeding, which tends to reduce an infant's chances of obesity in later life.

As a consequence of these shifts, the average weight of Americans increased throughout the century. But because many were underweight in the earlier years, the epidemic of obesity did not become apparent until the 1980s, when these historical developments apparently reached critical mass. Dietary fat has not played a major role in the epidemic. Although clinical trials have shown that reducing dietary fat leads to weight reduction, the average amount consumed has declined in recent decades. Heavy television viewing by children is linked to obesity, yet there is no definitive proof of a causal relation. The decline in smoking and the popularity of eating out—restaurants typically serve extra-large portions—have also been blamed, but the evidence remains contradictory.

Susceptibility to obesity tends to decline as income rises, with well-to-do Americans more likely to follow a goal of modish thinness. Women tend to be more susceptible than men because they are less physically active and because many are unable to return to their prepregnancy weight after childbirth. Income disparity may explain why African- and Mexican-Americans have a higher prevalence of obesity than white Americans, although genetic and cultural factors may also play a role. For instance, some data suggest that obesity may be more socially acceptable among blacks than among whites.

The U.S. has been the trendsetter in a worldwide epidemic of obesity. Other developed countries have followed a similar trajectory, although none of them has yet achieved the levels seen in the U.S. Average weights are climbing at a fast rate in developing countries. Accompanying the rising prevalence of obesity is the prospect for a rapidly growing global epidemic of chronic disease, including, most particularly, type 2 diabetes. According to a theory advanced by economist Tomas J. Philipson of the University of Chicago and jurist Richard A. Posner of the U.S. Court of Appeals for the Seventh Circuit, the rise in obesity will only come to an end as income and education increase.



RODGER DOYLE; SOURCE FOR CHARTS AND TABLE: NATIONAL CENTER FOR HEALTH STATISTICS. DATA FOR NON-HISPANIC WHITES BEFORE 1976–1980 ARE ESTIMATED

Rodger Doyle can be reached at rodgerpdoyle@verizon.net

DEFINING OBESITY

The National Institutes of Health defines obesity as a body mass index (BMI) of 30 or greater, using the formula of weight in kilograms divided by the square of height in meters. Underweight is a BMI of less than 18.5; overweight is a BMI of 25 to 29.9.

Percent of American children who are obese (data from 1999 to 2000):

Age Range	Total	Boys	Girls
12 to 19	15.5	15.5	15.5
6 to 11	15.3	16	14.5
2 to 5	10.4	9.9	11

FURTHER READING

Why Have Americans Become More Obese? David M. Cutler, Edward L. Glaeser and Jesse M. Shapiro in *Journal of Economic Perspectives,* Vol. 17, No. 3, pages 93–118; Summer 2003.

The Long-Run Growth in Obesity as a Function of Technological Change. Tomas J. Philipson and Richard A. Posner in *Perspectives in Biology and Medicine,* Vol. 46, No. 3, Supplement, pages S87–S107; 2003.

The Pediatric Obesity Epidemic: Causes and Controversies. Arnold H. Slyper in *Journal of Clinical Endocrinology & Metabolism,* Vol. 89, No. 6, pages 2540–2547; June 2004.

BRAD HINES

It's Dogged as Does It

Retracing Darwin's footsteps in the Galápagos shatters a myth but reveals how revolutions in science actually evolve By MICHAEL SHERMER

Among the many traits that made Charles Darwin one of the greatest minds in science was his pertinacious personality. Facing a daunting problem in natural history, Darwin would obstinately chip away at it until its secrets relented. His apt description for this disposition came from an 1867 Anthony Trollope novel in which one of the characters opined: "There ain't nowt a man can't bear if he'll only be dogged.... It's dogged as does it." Darwin's son Francis recalled his father's temperament: "Doggedness expresses his frame of mind almost better than perseverance. Perseverance seems hardly to express his almost fierce desire to force the truth to reveal itself."

Historian of science Frank J. Sulloway of the University of California, Berkeley, has highlighted Darwin's dogged genius in his own tenacious efforts to force the truth of how Darwin actually pieced together the theory of evolution. The iconic myth is that Darwin became an evolutionist in the Galápagos when he discovered natural selection operating on finch beaks and tortoise carapaces, each species uniquely adapted by food type or island ecology. The notion is ubiquitous, appearing in everything from biology textbooks to travel brochures, the latter inveigling potential travelers to visit the mecca of evolutionary theory and walk in the tracks of St. Darwin the Divine.

In June 2004 Sulloway and I did just that, spending a month retracing some of Darwin's fabled footsteps. Sulloway is one sagacious scientist, but I had no idea he was such an intrepid field explorer until we hit the lava on San Cristóbal to reconstruct the famous naturalist's explorations there. Doggedness is the watchword here: with a sweltering equatorial sun and almost no freshwater, it is not long before 70-pound water-loaded packs begin to buckle knees and strain backs. Add hours of daily bushwhacking through dry, dense, scratchy vegetation, and the romance of fieldwork quickly fades.

Yet the harder it got, the more resolute Sulloway became. He actually seemed to enjoy the misery, and this gave me a glimpse into Darwin's single-mindedness. At the end of one particularly grueling climb through a moonscapelike area Darwin called the "craterized district" of San Cristóbal, we collapsed in utter exhaustion, muscles quivering, and sweat pouring off our hands and faces. Darwin described a similar excursion as "a long walk."

Death permeates these islands. Animal carcasses are scattered hither and yon. The vegetation is coarse and scrappy. Dried and shriveled cacti trunks dot a bleak lava landscape so broken with razor-sharp edges that moving across it is glacially slow. Many people have died, from stranded sailors of centuries past to wanderlust-struck tourists of recent years.

Darwin ate his data on the voyage home.

Within days I had a deep sense of isolation and of life's fragility. Without the protective blanket of civilization, none of us is far from death. With precious little water and even less edible foliage, organisms eke out a precarious living, their adaptations to this harsh environment selected for over millions of years. These critters are hanging on by the skin of their adaptive radiations. A lifelong observer of, and participant in, the creation-evolution controversy, I was struck by how clear the solution is in these islands: creation by intelligent design is absurd. Why, then, did Darwin depart the Galápagos a creationist?

The Darwin Galápagos legend is emblematic of a broader myth that science proceeds by select "eureka!" discoveries followed by sudden revolutionary revelations, whereupon old theories fall before new facts. Not quite. Paradigms power perceptions. Sulloway discovered that nine months after departing the Galápagos, Darwin made this entry in his ornithological catalogue about his mockingbird collection: "When I see these Islands in sight of each other, & possessed of but a scanty stock of animals, tenanted by these birds, but slightly differing in structure & filling the same place in Nature, I must suspect they are only varieties." That is, similar *varieties* of fixed kinds, rather than the myth that he already knew that *evolution* was responsible for the creation of separate species. Darwin was still a creationist! This quotation explains why Darwin did not even bother to record the island locations of the few finches he collected (and in some cases mislabeled) and why, as Sulloway has pointed out, these now famous "Darwin finches" were never specifically mentioned in *On the Origin of Species.*

Darwin similarly botched his tortoise observations. Later, he recalled a conversation he had had while in the islands with the vice governor Nicholas O. Lawson, who explained that for the tortoises Lawson "could with certainty tell from which island any one was brought. I did not for some time pay sufficient attention to this statement, and I had already partially mingled together the collections from two of the islands." Worse, as Sulloway recounts humorously, Darwin and his mates ate the remaining tortoises on the voyage home. As Darwin later confessed: "I never dreamed that islands, about fifty or sixty miles apart, and most of them in sight of each other, formed of precisely the same rocks, placed under a quite similar climate, rising to a nearly equal height, would have been differently tenanted."

HISTORIANS OF SCIENCE Frank J. Sulloway (*left*) and Michael Shermer during their summit of Pan de Azúcar, Galápagos, which was Charles Darwin's first volcanic climb, made in September 1835.

SHERMER ATOP a collapsed lava bubble amid the volcanic flows of San Cristóbal, which can be seen in the upper areas of the aerial photograph. Darwin, who hiked up into these flows, deduced that the prominent tuff cone in the foreground had once been a separate island and became connected to the mainland through successive volcanic eruptions.

ROB SMITH (*top*); YANN ARTHUS-BERTRAND *Corbis* (*middle*); FRANK J. SULLOWAY (*bottom*)

Through careful analysis of Darwin's notes and journals, Sulloway dates Darwin's acceptance of the fact of evolution to the second week of March 1837, after a meeting Darwin had with the eminent English ornithologist John Gould, who had been studying his Galápagos bird specimens. With access to museum ornithological collections from areas of South America that Darwin had not visited, Gould corrected a number of taxonomic errors Darwin had made (such as labeling two finch species a "Wren" and an "Icterus") and pointed out to him that although the land birds in the Galápagos were endemic to the islands, they were notably South American in character.

Darwin left the meeting with Gould, Sulloway concludes, convinced "beyond a doubt that transmutation must be responsible for the presence of similar but distinct species on the different islands of the Galápagos group. The supposedly immutable 'species barrier' had finally been broken, at least in Darwin's own mind." That July, Darwin opened his first notebook on *Transmutation of Species,* in which he noted: "Had been greatly struck from about Month of previous March on character of S. American fossils—and species on Galapagos Archipelago. These facts origin (especially latter) of all my views." By 1845 Darwin was confident enough in his data to theorize on the deeper implications of the Galápagos: "The archipelago is a little world within itself, or rather a satellite attached to America, whence it has derived a few stray colonists, and has received the general character of its indigenous productions.... Hence both in space and time, we seem to be brought somewhat near to that great fact—that mystery of mysteries—the first appearance of new beings on this earth."

For a century and a half, Darwin's theory has steadfastly explained more disparate facts of nature than any other in the history of biology; the process itself is equally dogged, as Darwin explained: "It may be said that natural selection is daily and hourly scrutinising, throughout the world, every variation, even the slightest; rejecting that which is bad, preserving and adding up all that is good; silently and insensibly working, whenever and wherever opportunity offers." Doggedly so. SA

Michael Shermer is publisher of Skeptic *(www.skeptic.com). His upcoming book is* Why Darwin Matters.

Teach the Science

Wherever evolution education is under attack by creationist thinking, Eugenie Scott will be there to defend science—with rationality and resolve By STEVE MIRSKY

Federal court had just been dismissed in Harrisburg, Pa., on September 26, 2005, the first day of the Dover intelligent design trial. Commentators dubbed it Scopes II or III, depending on how many previous evolution education cases they knew of. The defendants, members of the Dover, Pa., school board, had required that a statement denigrating evolutionary theory be read to ninth-grade biology students and recommended so-called intelligent design be considered a viable and intellectually adequate alternative. Plaintiffs were parents in the school district who alleged that intelligent design, or ID, was in fact a religious construct and that presenting it to their children in a public school science class thus violated the establishment clause of the First Amendment to the U.S. Constitution.

STEVE MIRSKY

EUGENIE SCOTT: SISYPHUS WITH A SMILE

- **Executive director of the National Center for Science Education, she describes herself as Darwin's golden retriever, for her amiable defense of evolution in the classroom.**
- **Hosts an annual rafting trip through the Grand Canyon to counter one by creationists who use it to teach biblical flood geology.**
- **On who should be concerned about creationism: "Anybody who cares that the U.S. has a biologically literate society, with biotech, biomedicine, agriculture and other related technologies and industries."**

A steady rain forced plaintiffs, defendants, witnesses and media to huddle together under the overhang at the entrance to the Harrisburg Federal Building and Courthouse. Within a few feet of advocates who had minutes before put evolution itself on trial stood Eugenie Scott. As executive director of the National Center for Science Education (NCSE), she is the country's foremost defender of evolution education. She patiently explained to reporters why this trial was so important: "It's the first case that is considering the legality of the two current strategies of the antievolution movement."

The first strategy is advocacy for intelligent design—the notion that life or certain aspects of life are too complex to have arisen naturally and must therefore be the product of an intelligent designer. "Creation science was the original scientific alternative to evolution," says Scott, who turned 60 during the trial, "and ID is the scientific alternative to evolution du jour. And it's basically a subset of creation science. ID has never been on trial before."

The second strategy, casting doubt on evolutionary science, has roots in 1987, when the U.S. Supreme Court in *Edwards v. Aguillard* found by a 7–2 decision that creationism was religious and therefore ineligible for inclusion in public school biology curricula. In his majority opinion, Justice William J. Brennan wrote that teachers had the right to teach scientific alternatives to evolution, "which of course they do," Scott explains. "If there were any, they would have the right to teach them."

But Justice Antonin Scalia, joined in his dissent by Chief Justice William H. Rehnquist, wrote that "whatever scientific evidence there may be against evolution" could also be "presented in their schools." A tactic, then, is to portray the lack of certitude about every last detail of evolution—so-called gaps or honest disagreements between evolutionary biologists about mechanisms—as evidence against it.

The Dover trial involved arguments on both evidence against evolution and intelligent design. To Scott, "it's a dream condition because we can hopefully challenge both of these components." Scott's dream was apparently the defendant's nightmare. Fellows of the Discovery Institute, a Seattle-based pro–intelligent design group, were to appear as defense witnesses but withdrew, citing their desire to be represented by their own attorneys during depositions. That "they yanked the A team I think suggests that they're cutting their losses," Scott says.

The Dover trial was a dream condition, Eugenie Scott says—it challenged both intelligent design and doubts about evolution.

Dover was just the latest hot spot Scott has visited. The NCSE office in Oakland, Calif., includes a wall map of the U.S., with stickpins in the sites of challenges to evolution education. "There's a surprising amount in the midsection and in Maryland, Pennsylvania, Tennessee," she notes. "Then a cluster in California, in Texas and in Kansas, of course." Kansas, which remains a battleground over evolution education, is where Scott first got directly involved in the fight.

Shortly after joining the faculty of the University of Kentucky as a physical anthropologist in 1974, she attended a debate at the University of Missouri between her mentor, Jim Gavan, and Duane Gish, a leader in the then nascent scientific creationism movement. She began to collect creationist literature and to study adherents' methods. As a visiting professor at the University of Kansas in 1976, she was thus prepared to advise two biology professors who debated Gish and fellow creationist Henry Morris. Her "true baptism," as she calls it, came in 1980, when she advised the Lexington, Ky., Board of Education, which ultimately rejected a request to include the "balanced" teaching of origins.

Recognizing that the creationism movement would continue, a group of scientists and educators established the NCSE in 1981. "This was to be an organization that would focus on opposing creationism at the grassroots," explains Scott, who was on the periphery then, "because that's where the problem is. Education is decentralized, so the fight has to be local."

In 1986 she became the NCSE's executive director. Her current career bears strong similarities to an academic one. "I'm still teaching. I'm just teaching on a radio show, or I'm teaching a reporter the details. A lot of the same skills I had as a college professor are involved—taking complicated ideas and bringing them to the level so that whoever you're talking to can understand."

Along with intellectual rigor and stamina, Scott is known for her congeniality. Thomas Huxley was called Darwin's bulldog, leading to other canine analogies for evolution's defenders. Richard Dawkins, elegant and aggressive, has been called Darwin's greyhound. Scott thinks that the fast and focused Brown University biologist Ken Miller, a devout Catholic who was the first witness in the Dover case, is Darwin's border collie. "And I am Darwin's golden retriever," she says. "In my personal relationships with creationists, I have tried very hard to always keep things civil and never personal."

Being a happy warrior is both natural to Scott and probably the best way for her and her side to harness support. "To me, her most impressive accomplishments are the coalitions of very diverse people and organizations she has knit together in support of science education—especially the clergy," says Sean Carroll, a molecular biologist and geneticist at the University of Wisconsin–Madison. "Because when seriously religious people speak up in favor of evolution, people listen."

Total victory could be long in coming, with thousands of local school boards making curriculum decisions. In fact, the threat to public science education may be growing: astronomy and cosmology can also offend religious fundamentalists. Of her first American Astronomical Society meeting in 2005, she says: "I couldn't get five yards without somebody coming up to me and saying, 'Let me tell you about the problems I'm having teaching big bang, let me tell you about the problems I'm having teaching formation of the solar system, etc.' "

On December 20, 2005, Judge John Jones issued a blistering 139-page decision in favor of the plaintiffs, in which he referred to the "breathtaking inanity" of the school board's decision to require the antievolution disclaimer. He also forcefully noted that intelligent design is not science, "in the hope that it may prevent the obvious waste of judicial and other resources which would be occasioned by a subsequent trial." Scott declares Jones's finding a victory for science and education but also predicts the judge's hope will be dashed. "It's like a water bed," she says of antievolutionism. "You push it down in one place, and it bounces up in another." Indeed, the Kansas State Board of Education recently voted, 6–4, to allow intelligent design to be taught in public schools. Scott, it seems clear, won't be out of a job anytime soon. SA

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TABLETOP ACCELERATORS producing electron beams in the 100- to 200-million-electron-volt (MeV) range are just one type of machine made possible by plasma acceleration.

PLASMA ACCELERATORS

A new method of particle acceleration in which the particles "surf" on a wave of plasma promises to unleash a wealth of applications

By Chandrashekhar Joshi

CHIP SIMONS

Physicists use particle accelerators to answer some of the most profound questions about the nature of the universe. These gargantuan machines accelerate charged particles to nearly the speed of light and then smash them together, re-creating the conditions that existed when our universe was cataclysmically born in the big bang. By analyzing the debris of the collisions, physicists hope to understand how the seemingly disparate forces and particles that exist in our universe are all connected and described by a unified theory. Unfortunately, as they get closer and closer to solving this mystery of creation, physicists need particle accelerators of ever greater power (and expense).

The most powerful particle accelerator, now under construction at CERN, the European laboratory for particle physics on the French-Swiss border, is the 8.6-kilometer-diameter Large Hadron Collider (LHC). After the LHC is completed in 2007, the collisions of its two seven-trillion-volt proton beams should tell us what gives particles their mass [see "The Mysteries of Mass," by Gordon Kane; SCIENTIFIC AMERICAN, July 2005]. Other currently operating machines are attempting to explain why the universe contains more matter than antimatter and are giving us a peek into the primordial state of matter called a quark-gluon plasma. All these colliders are based on a bulky decades-old technology in which microwaves accelerate the particles.

Over the past 75 years these machines and their predecessors have produced remarkable discoveries about the nature of fundamental particles and the behavior of nuclear matter. Advances in the science and engineering of particle accelerators made that continual stream of revelations possible by allowing scientists to build machines whose energy was greater by roughly a factor of 10 every decade. Will such advances continue? The microwave-based machines may well be approaching the limits of what is technologically and economically feasible. In 1993 Congress canceled the $8-billion Superconducting Super Collider project, a 28-kilometer-diameter accelerator that would have had more than twice the power of the LHC. Many particle physicists now hope to follow the LHC with a 30-kilometer-long linear collider, but no one can predict if that proposed multibillion-dollar project will fare better than the Super Collider.

Perhaps just in time, new approaches to particle acceleration, using the fourth state of matter (after solid, liquid and gas) called a plasma, are showing considerable promise for realizing an accelerator for physics at the highest energies (100 billion electron volts and up). This plasma-based approach might dramatically reduce the size and cost of such an accelerator.

Giant accelerators operating near the high-energy frontier for physics research are just one part of the story. In addition, people use smaller machines for materials science, structural biology, nuclear medicine, fusion research, food sterilization, transmutation of nuclear waste, and the treatment of certain types of cancer. These smaller machines produce electron or proton beams with relatively low energy—in the 100-million- to one-billion-volt range—but still occupy large laboratory spaces. Extremely compact, or "tabletop," plasma accelerators promise to provide electron beams in this energy range.

TABLETOP PLASMA ACCELERATORS promise to provide electron beams for lower-energy APPLICATIONS.

Overview/*Surfing on Plasmas*

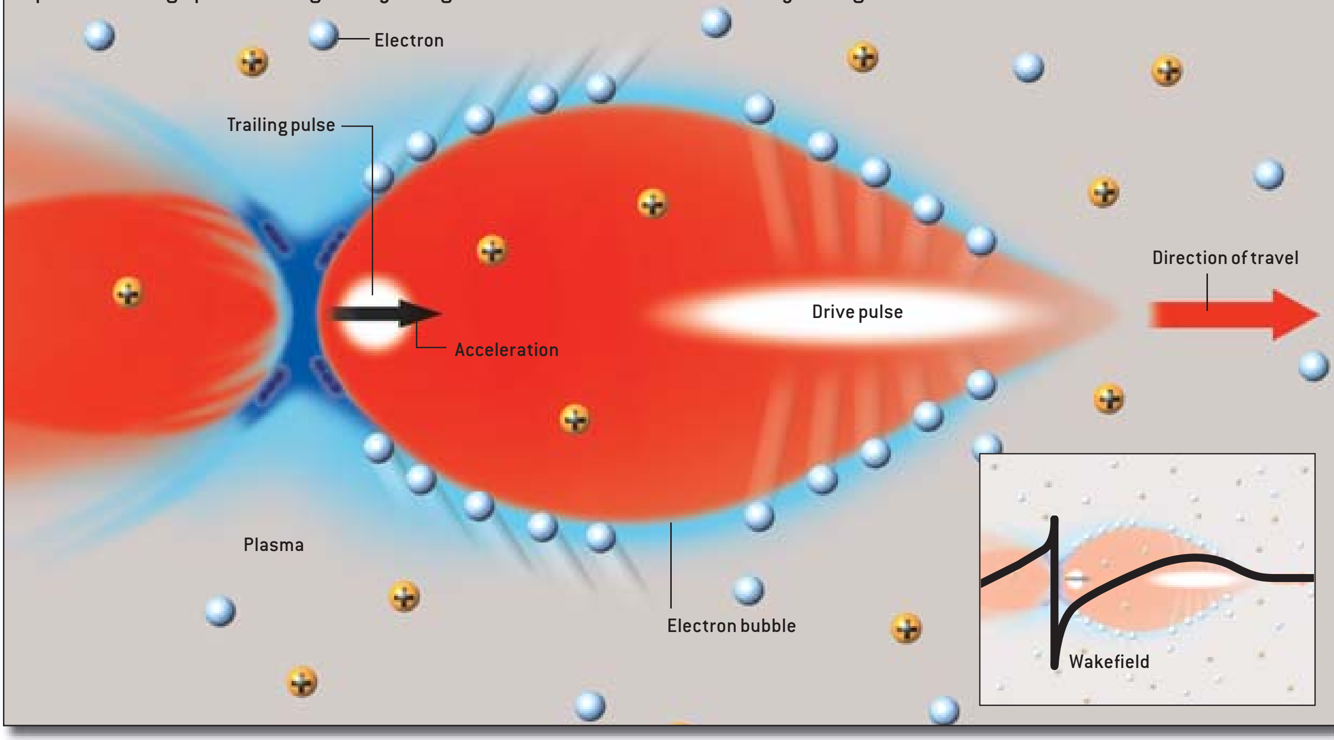
- For decades, particle colliders have used microwave cavities to propel particle beams to nearly the speed of light. That approach, exemplified by the 8.6-kilometer-diameter Large Hadron Collider, is reaching its technological and economic limits.
- A new technique, in which electrons or positrons gain energy by surfing on a wave in an ionized gas, or plasma, promises to slash the size and expense of these high-energy accelerators used by particle physicists to study questions such as the origins of mass in the universe. So far the method has been demonstrated in small laboratory experiments.
- The plasma machines will also enable construction of tabletop accelerators for a wide range of lower-energy applications, including materials science, structural biology, nuclear medicine and food sterilization.

Microwaves vs. Plasma

BEFORE I DETAIL the new technology, it helps to review some accelerator basics. Accelerators come in just a few broad types. First, they propel either lighter particles (electrons and positrons) or heavier ones (such as protons and antiprotons). Second, they can accelerate the particles in a single passage along a straight line or in many orbits around a circular ring. The LHC, for example, is a ring that collides two proton beams. The collider that physicists hope to build after the LHC will be a linear collider of electrons and positrons. The energy at the collision point will initially be in the neighborhood of one-half TeV (trillion electron volts). At such energies, electrons and positrons must be accelerated in a straight line; accelerating them in a ring would result

THE BUBBLE REGIME

Wakefield accelerator relies on a charge disturbance known as a wakefield to provide the driving force. The drive pulse, which can be a short pulse of either a laser or an electron beam, blows the electrons (*blue*) in an ionized gas, or plasma, outward—leaving behind a region of positive charge (*red*). The positive charge pulls the negatively charged electrons back in behind the drive pulse, forming an electron bubble around the positive region. Along the axis that the beam propagates, the electric field (*plotted below*) resembles a very steep ocean wave about to break. This field—the wakefield—causes a trailing pulse of electrons caught near the rear of the bubble to feel a very strong forward acceleration.



in excessive energy loss from a process called synchrotron radiation. Linear acceleration of electrons and positrons is what plasma-based accelerators are most suited for.

A conventional linear collider accelerates its particles with an electric field that moves along in synchrony with the particles. A structure called a slow-wave cavity (a metallic pipe with periodically placed irises) generates the electric field using powerful microwave radiation. The use of a metallic structure limits how large the accelerating field can be. At a field of 20 million to 50 million volts per meter, electrical breakdown occurs—sparks jump and current discharges from the walls of the cavities. Because the electric field has to be weaker than the threshold for breakdown, it takes a longer acceleration path to achieve a specific energy. For example, a trillion-volt beam would require an accelerator 30 kilometers long. If we could accelerate particles far more quickly than is allowed by the electrical breakdown limit, the accelerator could be made more compact. That is where plasma comes in.

In a plasma accelerator, the role of the accelerating structure is played by the plasma, an ionized gas. Instead of being a problem, electrical breakdown is part of the design because the gas is broken down to begin with. The power source is not microwave radiation but is either a laser beam or a charged particle beam.

At first sight, laser beams and charged particle beams do not seem well suited for particle acceleration. They do have very strong electric fields, but the fields are mostly perpendicular to the direction of propagation. To be effective, the electric field in an accelerator has to point in the direction that the particle travels. Such a field is called a longitudinal field. Fortunately, when a laser or charged particle beam is sent through a plasma, interaction with the plasma can create a longitudinal electric field.

The process works in this way: A plasma as a whole is electrically neutral, containing equal amounts of negative charge (electrons) and positive charge (ions). A pulse from an intense laser or particle beam, however, creates a disturbance in the plasma. In essence, the beam pushes the lighter electrons away from the heavier positive ions, which in turn get left behind, creating a region of excess positive charge and a region of excess negative charge [*see box above*]. The disturbance forms a wave that travels through the plasma at nearly the speed of light. A powerful electric field points from the positive to the negative region and will accelerate any charged particles that come under its influence.

A plasma medium can support accelerating electric fields of fantastic

GEORGE RETSECK

magnitude. A plasma containing 10^{18} electrons per cubic centimeter (an unexceptional number) can generate a wave with a peak electric field of 100 billion volts per meter. That is more than 1,000 times more intense than the accelerating gradient in a typical conventional accelerator powered by microwaves. Now the catch: the wavelength of a plasma wave is only 30 microns, whereas the typical microwave wavelength is 10 centimeters. It is very tricky to place a bunch of electrons in such a microscopic wave.

The late John M. Dawson of the University of California, Los Angeles, first proposed this general method of using plasmas to accelerate particles in 1979. It took more than a decade before experiments demonstrated electrons surfing plasma waves and gaining energy. Three different technologies—plasmas, accelerators and lasers—had to be tamed and made to work together. My group at U.C.L.A. accomplished that feat unambiguously in 1993. Since then, progress in this field has been explosive. Two techniques in particular, called the laser wakefield accelerator and the plasma wakefield accelerator, are showing spectacular results. The laser wakefield looks promising for yielding a low-energy tabletop accelerator, and the plasma wakefield has the potential to produce a future collider at the energy frontier of particle physics.

Pulses of Light

TABLETOP PLASMA accelerators are made possible today by intense, compact lasers. Titanium-sapphire lasers that can generate 10 terawatts (trillion watts) of power in ultrashort light pulses now fit on a large tabletop [see "Extreme Light," by Gérard A. Mourou and Donald Umstadter; SCIENTIFIC AMERICAN, May 2002].

In a laser-powered plasma accelerator, an ultrashort laser pulse is focused into a helium jet that is a couple of millimeters long. The pulse immediately strips off the electrons in the gas, producing a plasma. The radiation pressure of the laser bullet is so great that the much lighter electrons are blown outward in all directions, leaving behind the more massive ions. These electrons cannot go very far, because the ions pull them back inward again. When they reach the axis that the laser pulse is traveling along, they overshoot and end up traveling outward again, producing a wavelike oscillation [*see box on preceding page*]. The oscillation is called a laser wakefield because it trails the laser pulse like the wake produced by a motorboat.

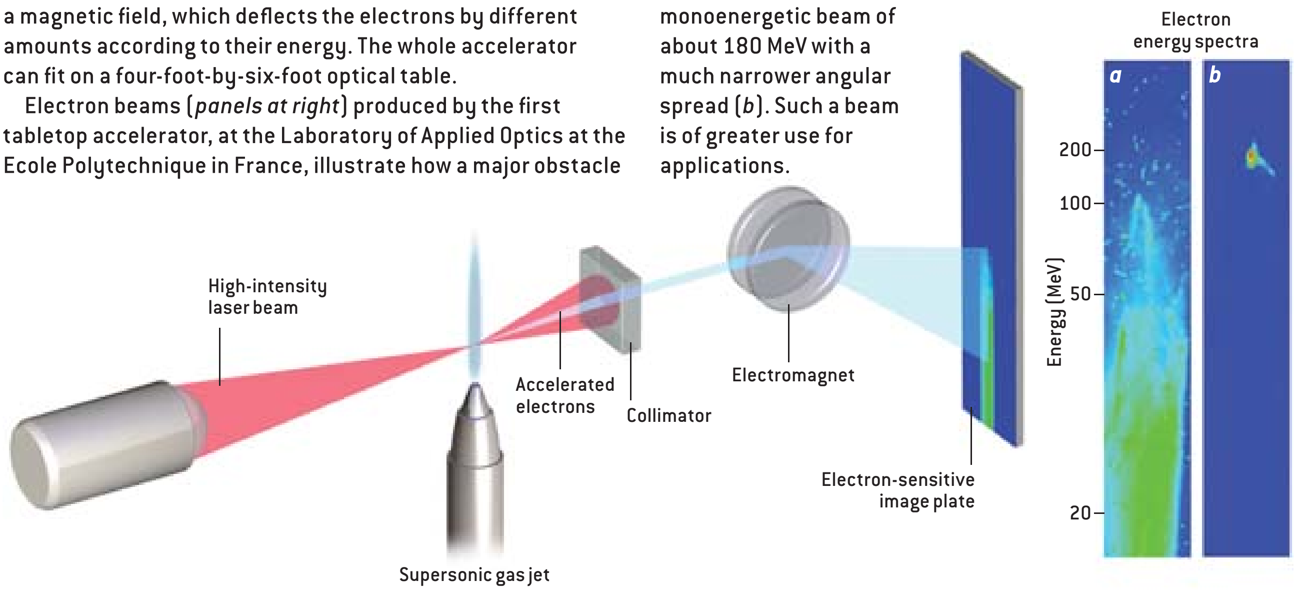
The electrons actually form a bubblelike structure. Near the front of the bubble is the laser pulse that creates the plasma, and inside the rest of the bubble are the plasma ions. This bubble structure is microscopic, about 10 microns in diameter. The electric field in the bubble region resembles an ocean wave but is much steeper. Although other structures are also possible, using the bubble regime appears to be the most robust way to accelerate electrons.

If a device such as an electron gun introduces an external electron close to where there is an excess of electrons in the plasma, the new particle will experience an electric field pulling it toward

LASER WAKEFIELD ACCELERATOR

A tabletop plasma accelerator consists of a high-intensity laser beam focused on a supersonic jet of helium gas (*left*). A pulse of the beam produces a plasma in the gas jet, and the wakefield accelerates some of the dislodged electrons. The resulting electron pulse is collimated and passed through a magnetic field, which deflects the electrons by different amounts according to their energy. The whole accelerator can fit on a four-foot-by-six-foot optical table.

Electron beams (*panels at right*) produced by the first tabletop accelerator, at the Laboratory of Applied Optics at the Ecole Polytechnique in France, illustrate how a major obstacle was overcome. Although some electrons were accelerated to 100 MeV, the electron energies ranged all the way down to 0 MeV (*a*). Also, the beam diverged by about a full degree. In contrast, the results from the recently discovered "bubble" regime showed a monoenergetic beam of about 180 MeV with a much narrower angular spread (*b*). Such a beam is of greater use for applications.

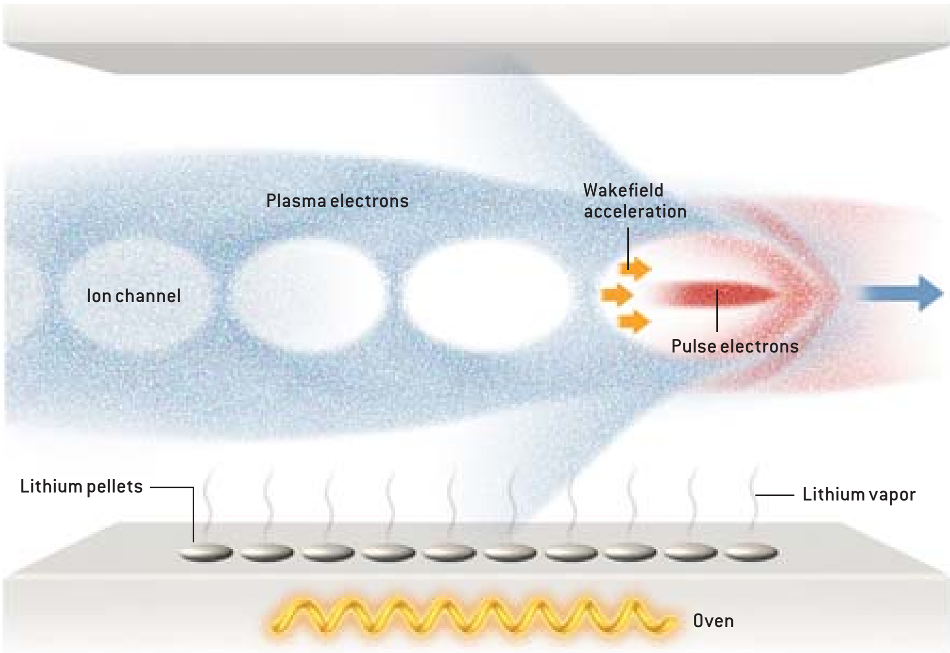


GEORGE RETSECK (*illustration*); SOURCE: VICTOR MALKA (*spectra*)

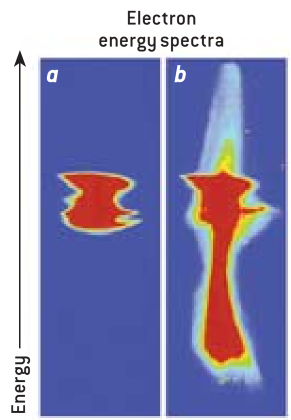
PLASMA AFTERBURNER

Plasma wakefield acceleration was recently demonstrated in an experiment using a beam of the Stanford Linear Collider (SLC). The accelerator added 4 GeV of energy to an electron beam in just 10 centimeters—an energy gain that would require a 200-meter section of a conventional microwave accelerator.

In the experiment, an oven vaporized lithium pellets. An intense electron pulse (*red*) ionized the vapor to produce a plasma. The pulse blew out the plasma electrons (*blue*), which then set up a wakefield, or a charge disturbance, behind the pulse. Electrons located in that wakefield experienced powerful acceleration (*orange arrows*).



In the absence of the lithium (*a*), SLC's 30-GeV beam was quite monoenergetic (energy is plotted vertically). After passing through 10 centimeters of lithium plasma (*b*), most of the beam particles lost energy in generating the plasma wakefield (*red tail*). The wakefield accelerated a small number of electrons that happened to be at the back of the pulse to higher energy (*blue region at top*).



GEORGE RETSECK (*illustration*); STANFORD LINEAR ACCELERATOR CENTER, UNIVERSITY OF CALIFORNIA, LOS ANGELES, AND UNIVERSITY OF SOUTHERN CALIFORNIA (*spectra*)

the positive charges inside the bubble. The wave moves along at light speed, so the electron has to be injected close to this velocity to catch the wave and gain energy from it. We know from the theory of relativity that any further increase in the electron's energy mostly comes from an increase in the mass of the particle and not its speed. The electron therefore does not significantly outrun the plasma wave. Instead it surfs the wave, gaining energy all the way. Some of the electrons from the plasma itself are also trapped and accelerated in this way, like foam caught on a cresting ocean wave.

In 2002 Victor Malka and his group at the Ecole Polytechnique's Laboratory of Applied Optics in France showed that a beam of 10^8 electrons could be generated using a laser-driven wakefield. The beam was well collimated, that is, tightly focused. Unfortunately, the accelerated electrons had a very wide range of energies—from one to 200 million-electron volts (MeV). Most applications require a beam of electrons that are all at the same energy.

This energy spreading occurred because the electrons were trapped by the wakefield wave at various locations and at different times. In a conventional accelerator, particles to be accelerated are injected into a single location near the peak of the electric field. Researchers thought that such precise injection was impossible in a laser wakefield accelerator because the accelerating structure is microscopic and short-lived.

Serendipity came to the rescue. In 2004 three competing groups from the U.S., France and the U.K. simultaneously stumbled on a new physical regime in which self-trapped electrons surf as a single group, all reaching the same energy. The three groups each used a higher-power laser than before—10 terawatts and above. When such a powerful laser pulse propagates through the plasma, it becomes both shorter and narrower, creating a large electron bubble that traps electrons from the plasma. These self-trapped electrons are so numerous that they extract a significant amount of energy from the wake and thus turn off further trapping. Those electrons with the highest energy begin to outrun the wake. Thus, higher-ener-

THE AUTHOR

CHANDRASHEKHAR JOSHI is professor of electrical engineering at the University of California, Los Angeles. He directs the Center for High Frequency Electronics and the Neptune Advanced Accelerator Research Facility at U.C.L.A. A pioneer in advanced acceleration techniques, Joshi is well known for his contributions to nonlinear optics of plasmas, intense laser-matter interactions, and applications of plasma science to fusion, accelerators and light sources. He enjoys travel and hiking.

gy electrons in the front begin to lose energy even as lower-energy electrons in the back are still gaining energy.

The result is a beam of electrons with a narrow energy spread. In Malka's experiments, for example, the energy spread was reduced from 100 percent to only 10 percent with up to 10^9 electrons per beam. The angular spread of the beam was also much narrower than in earlier experiments—comparable to the best beams produced by conventional microwave linear accelerators. The resulting electron beam (actually a pulse) had a length of only 10 femtoseconds (10^{-14} second), the shortest ever produced by an accelerator, making it attractive as a potential radiation source for resolving ultrafast chemical and biological processes. The electron pulse could be directed onto a thin metal target to produce a correspondingly short x-ray pulse. In the next year or two, I expect to see applications of x-rays from tabletop accelerators demonstrated.

How might one further increase the energy of the electron beam to produce a billion-electron-volt (GeV) laser wakefield accelerator? One needs to create a plasma wave that persists over a distance of about one centimeter instead of just a couple of millimeters. The laser beam that excites the wave therefore must be kept intense in the plasma for a longer time by guiding it in what is called a plasma fiber. A particularly promising approach is the use of a preformed plasma fiber, which researchers at Lawrence Berkeley National Laboratory are pursuing. In this method the electrons have a lower density along the plasma's axis. This causes the plasma channel to have a higher refractive index along its axis than at its edges—just the right condition for the channel to act like an optical fiber to guide the laser beam. The Berkeley experiments have already shown that such channels generate monoenergetic electron beams. Further improvements in this approach are likely to produce the first GeV-class tabletop plasma accelerator in the very near future.

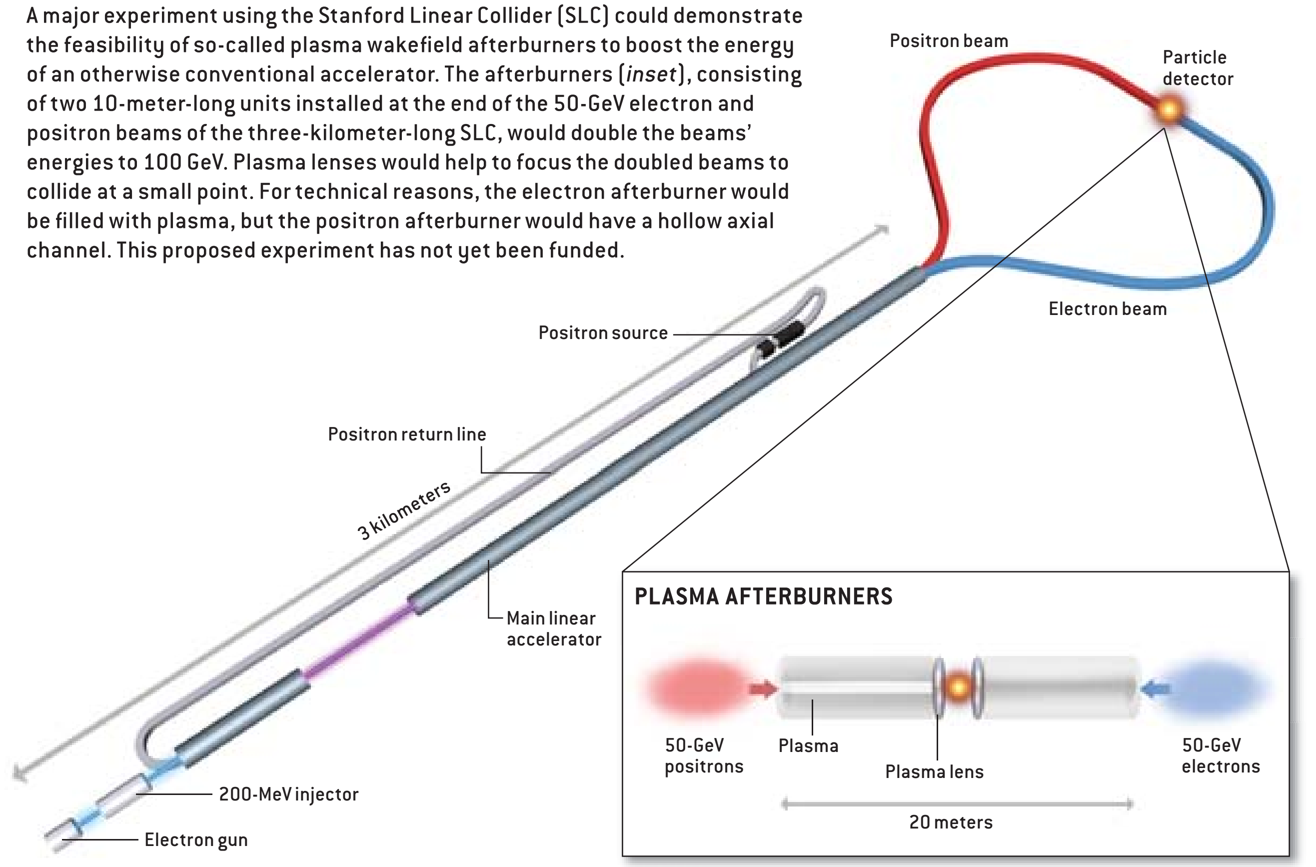
Scaling Up to the Energy Frontier

HOW CAN THESE centimeter-scale laser-driven plasma accelerators be extended to generate the TeV energies that are of interest to particle physicists? One approach would be to string together hundreds of compact laser-plasma acceleration modules, each providing a net energy gain of a few GeV. This design, called staging, is how microwave accelerators are combined to produce high energies. The problems associated with staging of plasma accelerators, however, are enormously complicated.

Instead the approach currently favored is the so-called plasma afterburner, in which a single plasma wakefield accelerator stage doubles the output en-

BOOSTING A CONVENTIONAL ACCELERATOR

A major experiment using the Stanford Linear Collider (SLC) could demonstrate the feasibility of so-called plasma wakefield afterburners to boost the energy of an otherwise conventional accelerator. The afterburners (*inset*), consisting of two 10-meter-long units installed at the end of the 50-GeV electron and positron beams of the three-kilometer-long SLC, would double the beams' energies to 100 GeV. Plasma lenses would help to focus the doubled beams to collide at a small point. For technical reasons, the electron afterburner would be filled with plasma, but the positron afterburner would have a hollow axial channel. This proposed experiment has not yet been funded.



GEORGE RETSECK

ergy of a conventional accelerator. In this approach, a conventional accelerator raises two electron or positron pulses to several hundred GeV. The first pulse (called the driver) contains three times as many particles as the second, trailing pulse. Both the driver and the trailing pulses are typically only 100 femtoseconds long and are separated by about 100 femtoseconds. As in a laser wakefield accelerator, when the driver pulse is focused into the plasma, it produces a wakefield bubble (provided that the beam is denser than the plasma). The process is the same as in the laser wakefield case, except now the particle beam's electric field does the pushing instead of the laser beam's radiation pressure. The electron bubble encloses the trailing beam, which is rapidly accelerated by the longitudinal component of the resulting electric field.

The plasma wakefield accelerator is causing a great deal of excitement among physicists who are working on advanced acceleration techniques. Three critical advances have made this scheme extremely attractive. These advances came from a team of scientists at U.C.L.A., the University of Southern California and the Stanford Linear Accelerator Center (SLAC) using the beams from the Stanford Linear Collider.

First and foremost, these scientists got around the problem of laser-driven plasma accelerators being only a few millimeters in length: they made a meter-long plasma accelerator for both electrons and positrons. It took great skill to keep the driver beams stable over such a length. Second, they demonstrated greater than 4 GeV of energy gain for electrons in just 10 centimeters. This energy gain was limited only by practical considerations and not by any scientific issues, which means that it can be increased simply by elongating the plasma.

Finally, they showed that plasma could further sharpen an already focused electron or positron beam by a factor of at least two. The improvement is significant for a collider, in which the accelerated particles must be focused to a very small spot. The more tightly focused the beams are, the more collisions the collider produces. For a collider, the rate of collisions is as vital a parameter as the total energy.

These breakthroughs have fueled speculation about the scalability of the plasma scheme to the energy frontier, but first the technique must be tested using a currently available accelerator as the first stage. For example, a pair of plasma wakefield devices could be installed on either side of the collision point of the Stanford Linear Collider. That would double the energies of the beams from the present 50 GeV to 100 GeV. Each plasma afterburner would be about 10 meters long. Although such a project is not yet funded, SLAC is proposing to the Department of Energy construction of a high-energy beam line called SABER to further this research.

I have described these plasma accelerators solely in terms of electron acceleration. To accelerate positively charged particles, such as positrons, the electric field must be reversed. The easiest way to do this is to use a positron driver beam. The positive charge of this beam draws the electrons of the plasma inward, and similar to before, they overshoot the central axis and form a bubble. The direction of the electric field is flipped compared with the electron-beam configuration I described earlier, as is required to accelerate a trailing beam of positrons.

In addition, these plasma-based machines can accelerate heavier particles such as protons. The one requirement is that the injected particles must be already traveling at nearly the speed of light, so they are not left behind by the plasma wave. For protons, that means an injection energy of several GeV.

Physicists are making rapid progress in the quest for a plasma accelerator. Although many of the fundamental physics issues are solved, the making of practical devices still poses formidable challenges. In particular, beam engineers must achieve adequate beam quality, efficiency (how much of the driver beam's energy ends up in the accelerated particles), and alignment tolerances (the beams must be aligned to within nanometers at the collision point). Finally, the repetition rate of the device (how many pulses can be accelerated each second) is important.

It took conventional accelerator builders 75 years to reach electron-positron collision energies in the range of 200 GeV. Plasma accelerators are progressing at a faster rate, and researchers hope to provide the new technology to go beyond the microwave systems for high-energy physics in just a decade or two. Much sooner than that, the companion laser wakefield technology will result in GeV tabletop accelerators for a rich variety of applications.

Surf's up! SA

The ACCELERATOR demonstrated greater than 4 GeV of energy gain for electrons in just 10 CENTIMETERS.

MORE TO EXPLORE

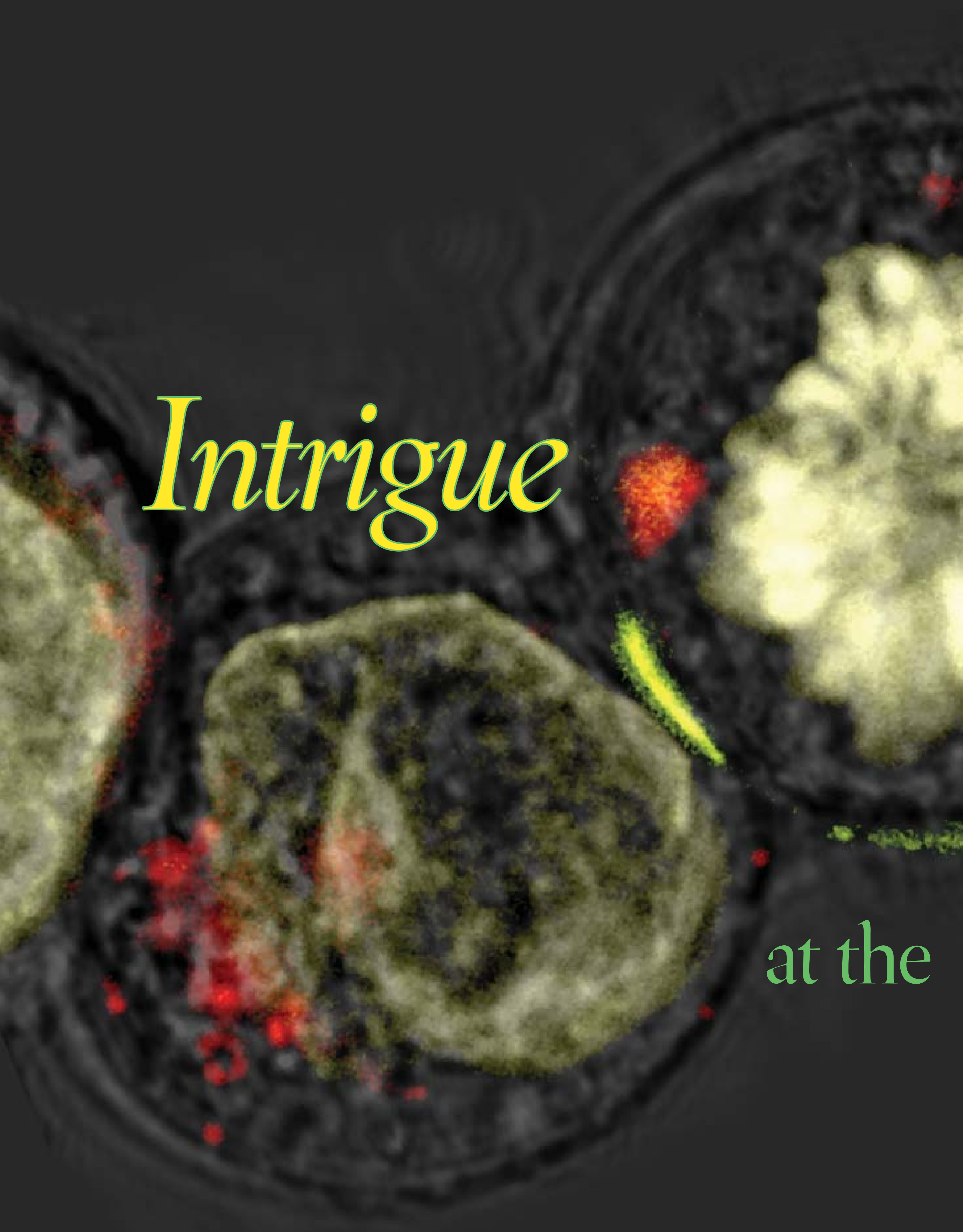
Plasma Particle Accelerators. John M. Dawson in *Scientific American,* Vol. 260, No. 3, pages 54–61; March 1989.

Plasma Accelerators at the Energy Frontier and on Tabletops. Chandrashekhar Joshi and Thomas Katsouleas in *Physics Today,* Vol. 56, No. 6; pages 47–53; June 2003.

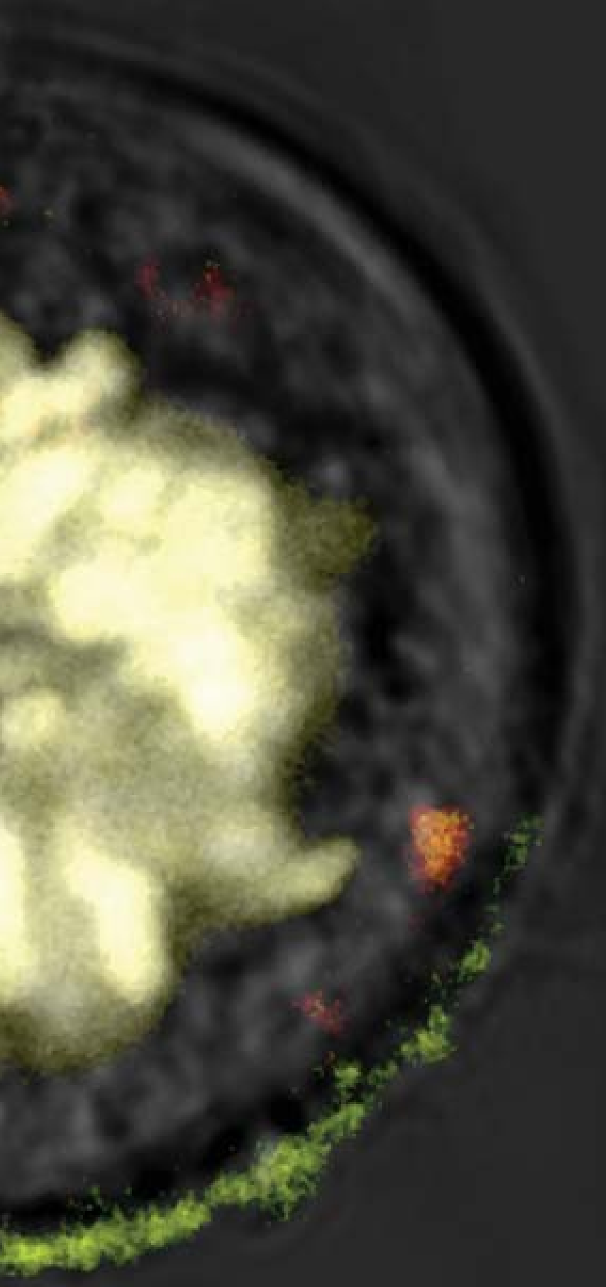
Accelerator Physics: Electrons Hang Ten on Laser Wake. Thomas Katsouleas in *Nature,* Vol. 431, pages 515–516; September 30, 2004. Also three research reports in the same issue.

The Lasers, Optical Accelerator Systems Integrated Studies (L'OASIS) Group at the University of California, Berkeley: **http://loasis.lbl.gov/**

Stanford's Plasma Wakefield Accelerator Experiment: **www.slac.stanford.edu/grp/arb/e164/index.html**



Intrigue at the



Images of interacting immune cells reveal structured connections similar to the ones neurons use to communicate. Studying these synapses is providing new insights into how the cells form an information-sharing network to fight disease

By Daniel M. Davis

Immune Synapse

PROTEINS (*yellow*) cluster at the point where two immune cells meet to trade information. The proteins at this synapse tell a natural killer cell (*bottom left*) that the B cell (*right*) is healthy and should be spared. For other cells that fail this test, the natural killer cell has acidic organelles (*red*) ready to move toward the synapse and deliver a lethal injection.

Comic-book fans know well that the most sought after editions are those in which a superhero appears for the first time. A comic book published in 1962 featuring the first appearance of Spider-Man, for example, recently sold at auction for $122,000. Sadly, publications representing the first appearance of an important scientific fact generally do not command similar prices, but to scientists these firsts are equally treasured.

Just such a moment occurred in 1995, when Abraham "Avi" Kupfer of the National Jewish Medical and Research Center in Denver stood before an unsuspecting group of a few hundred immunologists gathered for one of the prestigious Keystone symposia, named for a U.S. ski resort. Kupfer's presentation included the first three-dimensional images of immune cells interacting with one another. As the crowd watched in stunned silence, Kupfer showed them image after image of proteins organized into bull's-eye patterns at the area of contact between the cells.

To the group, the pictures were instantly understandable and unequivocal: like the synapses that form the critical junctures between neurons in neural communication networks, the contacts between the immune cells involved organized aggregates of proteins. Both outer rings of molecules keeping the cells adhered to one another and inner clusters of interacting proteins particular to the discussion between the cells were clearly visible.

The idea that immune cells—which must exchange and store information in the course of searching for and responding to disease—might share mechanisms with those consummate communicators, the cells of the nervous system, had been put forth before. But here, at last, was proof of structures to go with the theory. When Kupfer was finished, the room erupted in prolonged applause, followed by a barrage of questions.

A decade later these structured synapses formed by immune cells are still generating questions: about how cellular machinery or other forces produce the synaptic architecture, how the architecture, in turn, might regulate cell-to-cell communication, how its malfunction could lead to disease, and even how pathogens might exploit the mechanism to their own advantage.

Discovery of the immune synapse and its ongoing exploration has been made possible by new high-resolution microscopy techniques and computer enhancement of older imaging methods. Now the realization that a thought, the sensation of a touch, or the detection of a virus in the bloodstream all require similar choreography of molecules is providing a compelling new framework for understanding immunity.

Here, at last, were structures to go with the theory.

Seeking Direction

LONG BEFORE the immune synapse was seen, the possibility that immune cells might be able to target their communication was apparent. Scientists knew that immune cells secreted protein molecules called cytokines to talk with one another and with other types of cells. Yet at least some of these molecules did not seem to function like hormones, which diffuse throughout the body broadcasting their message widely. Rather cytokines could barely be detected in the blood and seemed to act only between cells that were touching.

This ability to trade chemical signals with just a particular neighbor is important for immune cells. Unlike neurons, which tend to form stable, long-term junctions with other cells, immune cells make fleeting contacts as they constantly roam the body seeking out signs of disease and exchanging information about present dangers. When an immune cell charged with identifying illness bumps into another cell, it may have only a couple of minutes to decide whether its target is healthy or not. If not, the immune cell, depending on its type, might kill the sick cell directly or raise an alarm, calling other immune soldiers to come do the job. Getting the communication wrong might lead to immune cells mistakenly killing healthy cells, as happens in autoimmune diseases such as multiple sclerosis, or allowing cancer cells to continue growing unchecked. Thus, immu-

Overview/*The Structured Dialogue*

- High-resolution microscope images of immune cells contacting other cells have revealed temporary membrane structures similar to the "synapse" connections nerve cells make with one another for communication.
- Investigations of these immune cell synapses focus on mechanisms that might control their configuration and on how the structures modulate communication between cells.
- Observing the real-time interactions of individual immune cells is a new avenue for understanding how they share and process information to defend the body against disease.

COURTESY OF BJÖRN ÖNFELT AND DANIEL M. DAVIS (*preceding pages*)

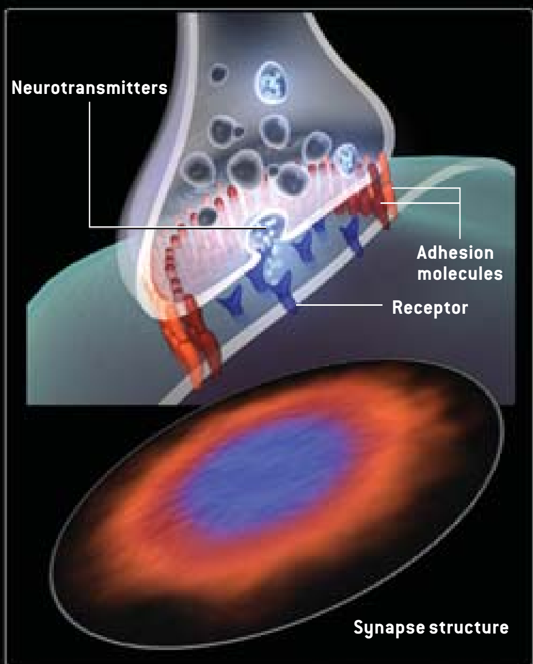
SYNAPSES UP CLOSE

Derived from two Greek words meaning "to join together" and "to fasten," a synapse is the point of contact where two cells exchange molecular signals and are often physically bound to one another by linked proteins. Between neurons, these connections are generally long-term, whereas immune cells make temporary bonds for quick dialogues. Immune synapse configurations can vary depending on cell type, and their formation proceeds in stages that may also regulate the cells' conversation.

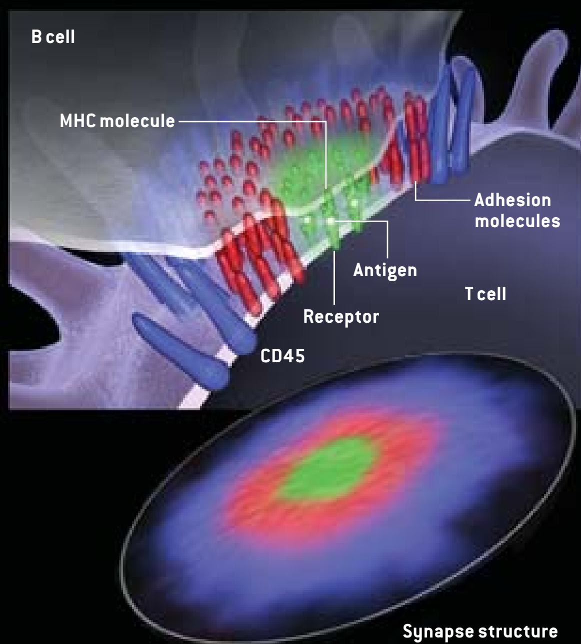
SYNAPTIC SIMILARITIES

In the classic synapse between two neurons, adhesion proteins hold the membranes of two interacting cells close together. When the first neuron is stimulated, packets of signaling molecules called neurotransmitters move toward the membrane to release their contents, which travel to receptors on the second neuron. In an immune synapse, adhesion molecules also hold cell membranes close together while other proteins interact. In this example, major histocompatibility complex (MHC) molecules on a B cell present protein fragments called antigens to a T cell's receptors. Proteins called CD45 that normally suppress signaling are shunted to the synapse periphery. Viewed as if from inside one of the cells, the synapse structures resemble bull's-eye patterns.

NEURAL SYNAPSE

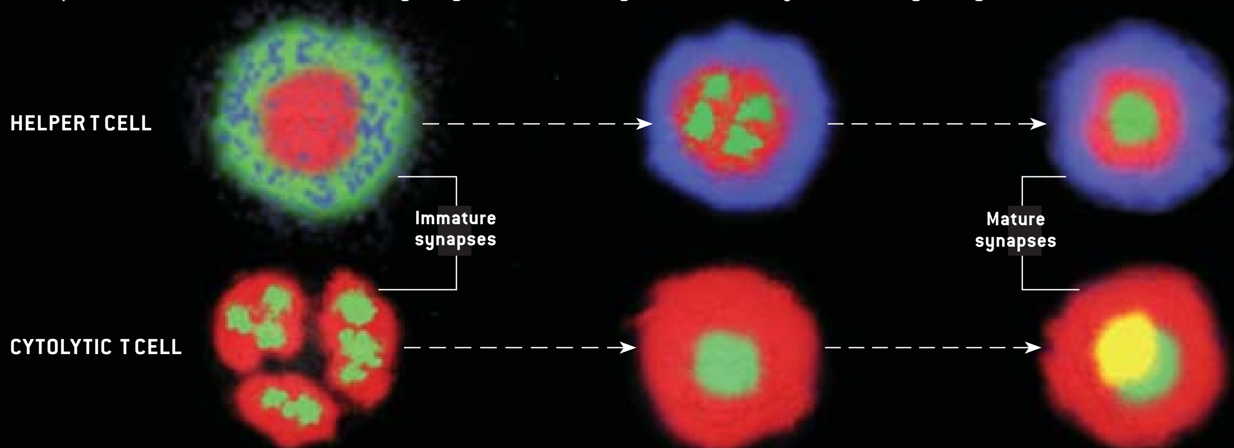


IMMUNE SYNAPSE



DYNAMIC DEVELOPMENT

The helper T cell's synapse starts with adhesion molecules (*red*) clustered at its center and receptors (*green*) in an outside ring, an order that will reverse in the mature synapse, where CD45 proteins (*blue*) form the outermost ring. Another immune cell type, the cytolytic T cell, is charged with killing unhealthy cells. When it meets one, its receptors and adhesion proteins begin to cluster, then form a ring. Finally, granules containing toxic molecules (*yellow*) travel from inside the cell to the center of the synapse to release their lethal load. Investigators want to learn what role these stages of synapse formation may play in regulating immune cell communication.



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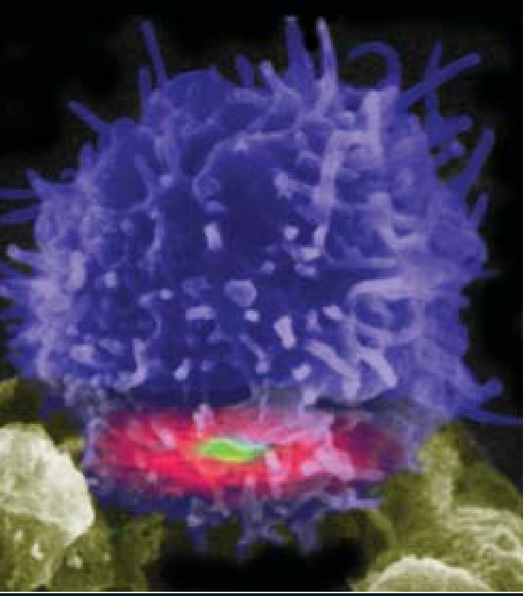


IMMUNE CELLS CONNECT for an exchange that will cause a T cell (*blue*) to become activated if it recognizes an antigen presented by the larger dendritic cell (*gold*). In this electron micrograph merged with a live-cell fluorescence image, T cell receptors interacting with antigen are clustered at the synapse center (*green*), and a ring of adhesion molecules (*pink*) holds the two cells together.

nologists have a keen interest in figuring out not only which molecules are involved in these dialogues but how they interact to enable such critical decisions.

In the early 1980s scientists in the Laboratory of Immunology at the National Institutes of Health began exploring the idea that a structured interface could allow immune cells to direct their secretion of cytokines to another cell. Because the cellular membranes, made largely from fat and protein molecules, are fluid, proteins could certainly move easily up to the point of contact between two cells and form an organized architecture there, as happens when neurons create a connection to another cell.

The NIH group's hypothesis grew from critical experiments showing that clustering specific proteins together at the surface of immune cells called T cells was sufficient to trigger activation of those cells. In a paper published in 1984, NIH investigator Michael A. Norcross first formally articulated the possibility that the nervous and immune systems have a common mechanism of communication through synapses. Unfortunately, it appeared in a journal that was not widely read, and some of his molecular details were off, so his early synaptic model of immune cell communication was soon forgotten. But curiosity about whether and how immune cells might target their messages remained.

In 1988 the late Charles A. Janeway, Jr., and his colleagues at Yale University performed a beautiful experiment to confirm that immune cells could indeed secrete proteins in a specific direction. They fitted T cells tightly into the pores of a membrane dividing a chamber containing solution. By adding a stimulant to the solution on only one side of the membrane, they activated the T cells, which subsequently started secreting proteins toward the source of the stimulant but not into the stimulant-free solution on the other side of the membrane.

Encouraged by this key observation, in 1994 NIH researchers William E. Paul and Robert A. Seder resurrected the idea that the immune synapse is the communicating junction between immune cells and other cells. They described the synapse as two cell surfaces in close proximity with a structured arrangement of receptor proteins on one cell surface, opposite their binding partners on the contacting cell. Acknowledging that immune cells move about far more than neurons, Paul spoke of the immune synapse as a "make and break" union in contrast with longer-term neuronal connections.

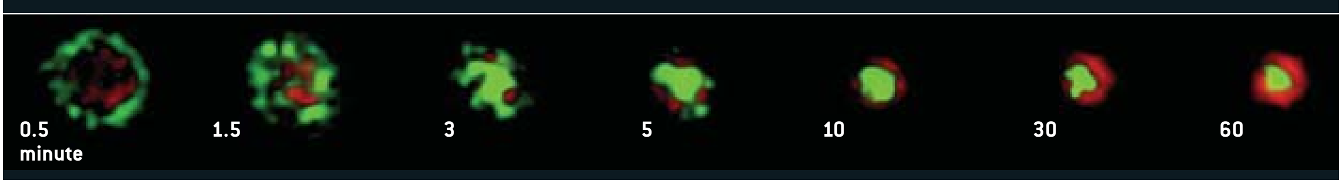
Thus, by the mid-1990s the immune synapse was established as a provocative concept for which a structure still needed to be seen experimentally. Then Avi Kupfer presented his slide show at the Keystone symposium. His images showed interactions between immune cells called antigen-presenting cells (APCs) that specialize in breaking up proteins belonging to an invader, such as a virus, and displaying the protein fragments to T cells, which become activated when they recognize one of the antigens. Hence, Kupfer dubbed the bull's-eye patterns of protein molecules formed at the interface of the two cells supramolecular activation clusters, or SMACs.

Independently, Michael L. Dustin, Paul M. Allen and Andrey S. Shaw of the Washington University School of Medicine in St. Louis, with Mark M. Davis of Stanford University, had also been imaging T cell activation, but with an interesting twist. Instead of observing two cells interacting together, they replaced the APC with a surrogate membrane composed of lipid molecules from a real cell laid out flat on a glass slide. To this glass-supported lipid membrane, they added the key proteins normally found at the surface of APCs, each tagged with a different colored fluorescent dye. They then watched the organization of these labeled proteins as T cells landed on the membrane [*see illustration below*].

Dustin's group also saw bull's-eye patterns of proteins emerge as the T cells surveyed the proteins within the supported membrane. Clearly, a structured synapse did not require the effort of two

IN ONE OF THE EARLIEST imaging experiments to reveal immune synapse structure, Michael L. Dustin and his colleagues employed fluorescently labeled proteins within an artificial cell membrane. These assume a synapse formation when an unseen T cell on the membrane's opposite side begins interacting with them.

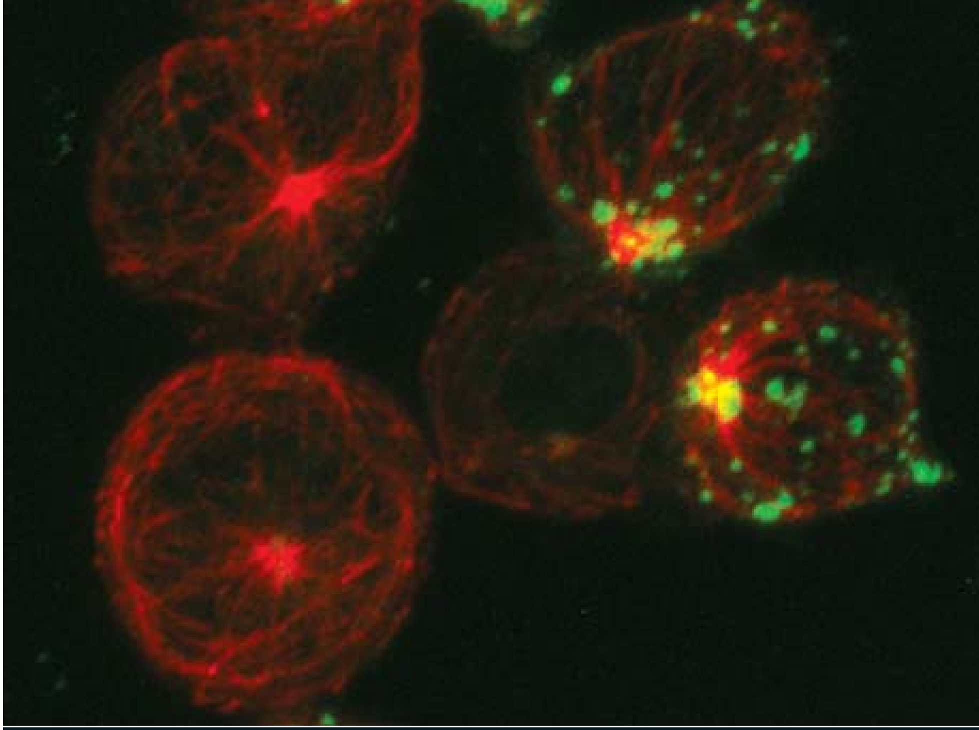
Proteins bearing an antigenlike molecule (*green*) first form an outer ring, with adhesion molecules (*red*) clustered at the center. Over a 60-minute interval, their arrangement reverses, mimicking stages of interaction at a synapse between T cells and real antigen-presenting cells.



COURTESY OF MICHAEL L. DUSTIN, REPRINTED WITH PERMISSION FROM *SCIENCE*, VOL. 285; ©1999 A.A.A.S. (*top*); COURTESY OF MICHAEL L. DUSTIN, REPRINTED WITH PERMISSION FROM "THE IMMUNOLOGICAL SYNAPSE: A MOLECULAR MACHINE CONTROLLING T CELL ACTIVATION," BY GRAKOUI ET AL., IN *SCIENCE*, VOL. 285; ©1999 A.A.A.S. (*bottom*) cells; instead it could form as one immune cell contacted and responded to an artificial array of proteins.

This work also revealed that the synapse itself is dynamic: arrangements of proteins change as the cell communication continues. For example, T cell receptors interacting with the antigen were first seen to accumulate in a ring surrounding a central cluster of adhesive proteins, creating an immature T cell synapse. Later, that structure inverted so that in the mature synapse the adhesive molecules formed an outer ring of the bull's-eye, surrounding a central cluster of interacting T cell receptors.

Since Kupfer and Dustin published their initial T cell synapse images, a variety of synapse structure patterns have also been seen between other types of immune cells. Indeed, my own contribution, while working with Jack Strominger of Harvard University in 1999, was to observe a structured synapse formed by a different kind of white blood cell—known as a natural killer (NK) cell—which helped to confirm the generality of their observations. Exploring how such changing arrangements of molecules occur and how they control immune cell communication is the new science opened up by the immune synapse concept.



TWO KILLER T CELLS (*right*) are captured as they prepare to destroy a diseased cell (*center*). Poisonous lytic proteins (*green*) cluster at the synapses between the T cells and their target, carried there by cytoskeletal proteins called microtubules (*red*). The lytic proteins will be injected into the target cell through the center of the synapse structures, which may also protect the T cells from poisoning themselves.

JANE C. STINCHCOMBE AND GILLIAN M. GRIFFITHS *University of Oxford*

The patterns may transmit, or at least reflect, information.

Deciphering the Dance

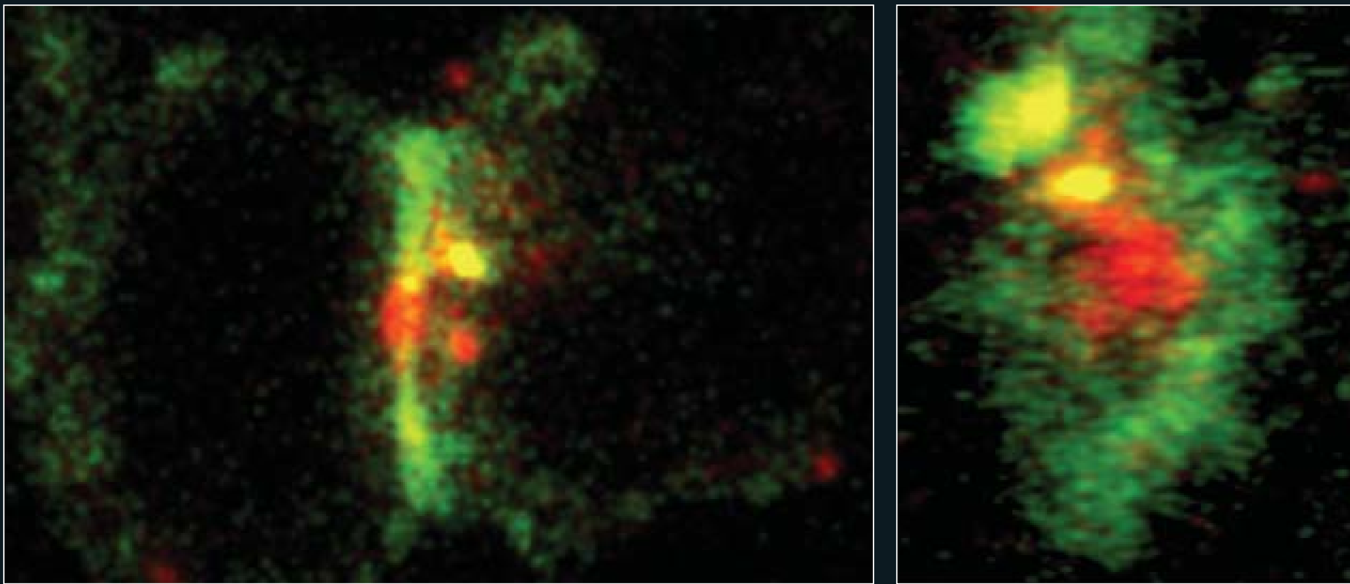
OBSERVATIONS of the structure of immune synapses immediately spurred researchers to investigate what makes the cellular proteins move to the contact point between the cells and organize themselves into specific patterns. One driver of protein movements in all cells is a remarkable network of filaments known as the cytoskeleton, which is made up of long chains of proteins that can extend or shrink in length. Tethered to the cell surface by adapter proteins, the cytoskeleton can push or pull the cell membrane, enabling muscles to contract or sperm to swim.

Experiments showed that when a cell's cytoskeleton was incapacitated by toxins, some proteins were no longer able to move toward the immune synapse, suggesting that movements of cytoskeletal filaments allow cells to control when and where the proteins accumulate at the synapse.

At least two other mechanisms could play a role in organizing proteins at the synapse, but the extent of their influence on immune cell communication is controversial. One set of proposals theorizes that small platforms made up of a few protein molecules each may be clustered in cell membranes and capable of moving around the cell surface together, most likely with help from the cytoskeleton. When these molecular "rafts" are brought together in the synapse with the key receptor proteins that detect disease in an opposing cell, their interaction could be what activates the immune cell. These preexisting platforms are contentious, however, because they are too small to see directly with an optical microscope, so evidence of their existence is somewhat indirect.

Another interesting possibility, with both indirect and direct support, is that the physical size of each type of protein forming the synapse can play an important role in determining where it goes when the cells come into contact. As proteins on one cell bind their counterparts on the opposing cell, the two cell membranes will be drawn together and the remaining gap between them will correspond to the size of the bound proteins. Thus, a central cluster of small proteins could bring the membranes close enough together to squeeze out larger proteins and hence segregate different types of protein to different regions of the synapse.

Arup K. Chakraborty and his colleagues at the University of California, Berkeley, used a mathematical model to test this idea by assessing the consequence of different-size proteins interacting across two opposing cell membranes. Although Chakraborty is not an



AS A HUMAN T CELL leukemia virus (*red*) moves to an uninfected T cell from an infected one (*heading from right to left above*), the adhesion molecule talin (*green*) is seen concentrating where the cell membranes meet. In a view from inside the infected T cell (*above right*), the structure's similarity to an immune synapse suggests that HTLV and other viruses that prey on immune cells, such as HIV, may take advantage of cellular communication mechanisms to spread from cell to cell.

immunologist, a colleague had shown him images from Dustin's work, and the mathematician says that he became fascinated by the intriguing spatial patterns his immune cells might be forming whenever he had the flu. His group's analysis suggested that in fact the difference in size between proteins could be enough to cause bigger and smaller proteins to cluster in separate regions of the immune synapse.

Of course, immunologists also want to know what, if anything, these protein movements "mean" in the context of immune cell communication. The answer could be "nothing": the earliest conception of the immune synapse being a kind of gasket enabling immune cells to direct their secretion of cytokines to a target cell may be the sole purpose of the structure. Increasingly, however, evidence is suggesting that the synapse may also have other functions that, depending on the cells involved, could include initiating communication, or terminating it, or serving to modulate the volume, so to speak, of signals between two cells.

In 2002 Kupfer (now at the Johns Hopkins School of Medicine) observed, for example, that signaling between T cells and antigen-presenting cells before the SMAC begins to take shape fostered adhesion between the two cells but that a SMAC was necessary for the cells' interaction to produce T cell responses.

Yet Shaw and Allen, along with Dustin, now at New York University, and their co-workers have shown that productive signaling between T cells and APCs starts before the T cell receptors have clustered in their final position at the center of the synapse. In fact, some of the communication is done before the mature structure forms, implying that the mature synapse pattern might signal an end to the conversation.

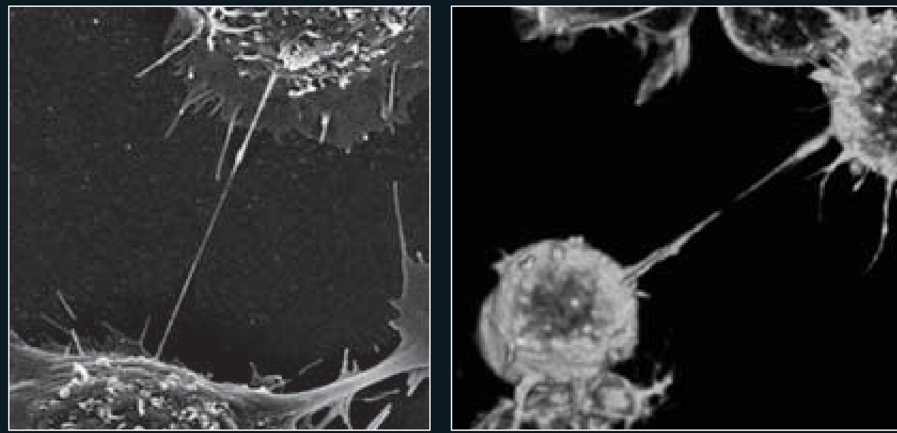
These investigators and others have also been exploring what role synapse architecture might play in regulating the volume of dialogues between T cells and APCs. By pulling receptors away from their surface membrane during signaling, T cells can prevent themselves from being lethally overstimulated by too much antigen. Experiments have shown that T cells can reduce the number of receptors present in the synapse architecture to dampen signaling, or when only a small amount of antigen is available, T cells may cluster their receptors more closely within the synapse to amplify the signal.

My own research group has been studying similar phenomena in natural killer cells, a type of immune cell that seeks and destroys cells damaged, for example, by a cancerous mutation or infected by a pathogen. These sick cells can lose the expression of some proteins on their surfaces, and NK cells recognize the loss as a sign of disease. We are finding that the amount of these proteins present on the target cell influences the pattern of the immune synapse formed by the NK cell. Different patterns correlate with whether or not the NK cell ultimately decides to kill the target cell, so the patterns may transmit, or at least reflect, information the NK cell uses to determine the extent of the target cell's illness.

Alongside these fascinating new insights into the possible functions of the immune synapse, disturbing news has emerged, too: another very recent observation is that the molecular dance that helps our immune cells communicate

THE AUTHOR

DANIEL M. DAVIS is a professor of molecular immunology at Imperial College London who specializes in high-resolution microscopy studies of immune cell interactions. Having started his scientific career as a physicist, he turned to immunology as an Irvington Institute postdoctoral research fellow in the Harvard University department of molecular and cellular biology. There, in 1999, he made the first images of the immune synapse structure in natural killer cells, which also provided the first sighting of synapse formation between two living cells. He has since written or co-authored more than 50 scientific papers in photophysics and immunology.



NANOTUBES made of cell membrane link two neural cells (*left*) and two immune cells (*right*). These recently discovered structures are still poorly understood but may constitute a novel mechanism for cells to communicate over long distances. Both immune and neural cells have been observed transferring proteins or calcium to one another through these nanotunnels, and viruses have been seen to travel from cell to cell within the tubes as well.

can be exploited by some viruses, including HIV. Charles R. M. Bangham of Imperial College London and his collaborators first showed that at the contact point between cells where viral particles are crossing over, proteins aggregate into a structure that resembles the immune synapse [*see illustration on opposite page*]. Several researchers have since observed similar "viral synapse" phenomena, and so it seems that viruses, which are known for hijacking cellular machinery to copy their genetic material, may also be able to co-opt cellular mechanisms for communication to propel themselves from one cell to another.

Healthy Voyeurism

THE DISCOVERY of the immune synapse has triggered a wave of research based on imaging immune cell interactions whose results have yet to be fully understood. But this fertile field is already producing new hypotheses and generating further research to test those. And the very idea of the synapse is already reshaping conceptions of the immune system, revealing it to be a sophisticated information-sharing network more like the nervous system than was previously realized.

Just using the synapse terminology to describe immune cell interactions has also encouraged neuroscientists and immunologists to compare notes, and they are finding that the two types of synapses use many common protein molecules. Agrin, for example, is an important protein involved in clustering other proteins at the synapse between neurons and muscle. Imaging experiments have shown that the same molecule also accumulates at immune synapses and can enhance at least some types of immune responses. Similarly, a receptor called neuropilin-1, known to participate in signaling between neurons, has been discovered at immune synapses. Experiments suggest that neuropilin-1 aids immune cells in their search for disease by helping to establish an immune synapse with other cells, but more research is needed to tease out the receptor's exact role in immunity.

My own team identified yet another intriguing similarity between neurons and immune cells when we observed that long tubes made of cell membrane readily form between immune cells and a variety of other cell types. Our investigation that led to this discovery was prompted by a report from German and Norwegian researchers of a similar phenomenon observed between neurons [*see illustration above*]. Neither we nor the neuroscientists know the function of these nanotubular highways, but finding out is a new goal for immunology and neuroscience alike.

These membrane nanotubes might, for example, constitute a previously unknown mechanism for immune cell communication by allowing directed secretion of cytokines between cells far apart. Simon C. Watkins and Russell D. Salter of the University of Pittsburgh School of Medicine have found that a population of immune cells could use such nanotubular highways to transmit calcium signals across vast (for cells) distances of hundreds of microns within seconds.

In the future, more studies of interactions among larger groups of immune cells could reveal additional aspects of immune cell communication networks. Imaging immune cell interactions as they traffic inside living organisms, rather than on a slide, is another important frontier for this line of research.

In a recent memoir, Nobel laureate John Sulston described using cutting-edge microscopy in the 1970s to understand worm development: "Now to my amazement, I could watch the cells divide. Those Nomarski images of the worm are the most beautiful things imaginable.... In one weekend I unraveled most of the postembryonic development of the ventral cord, just by watching."

High-resolution microscopy of immune cell interactions is still a very young field, and more surprises are surely in store. Virtually all the surface proteins involved in immune cells' recognition of disease have been identified and named. But the ability of scientists to now observe as these molecules play out their roles in space and time has revealed the immune synapse mechanism and reconfirmed the value of "just watching" as a scientific method. SA

MORE TO EXPLORE

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Neural and Immunological Synaptic Relations. Michael L. Dustin and David R. Colman in *Science,* Vol. 298, pages 785–789; October 25, 2002.

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THWARTING NUCLEAR TERRORISM

Many civilian research reactors contain highly enriched uranium that terrorists could use to build nuclear bombs

BY ALEXANDER GLASER AND FRANK N. VON HIPPEL

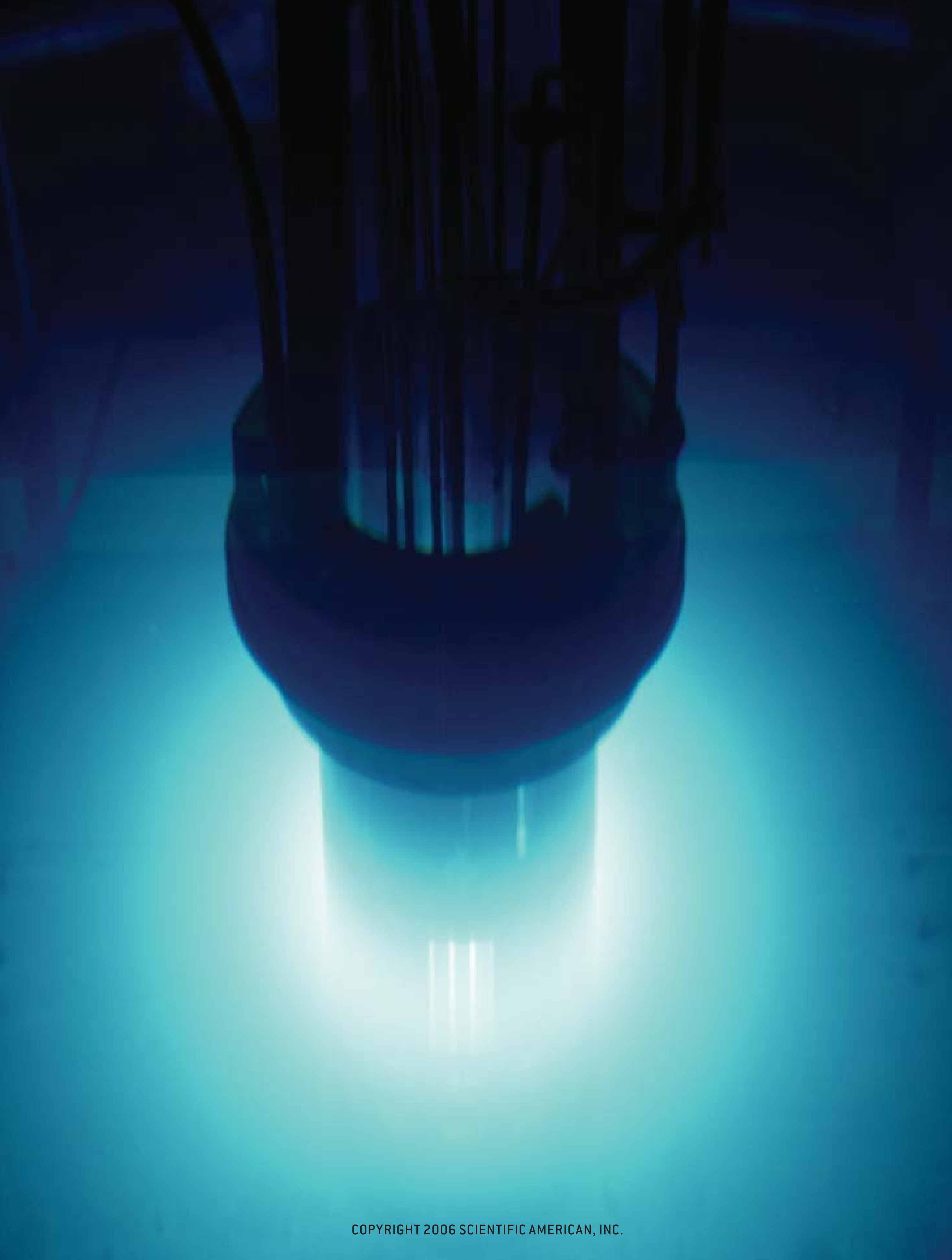
The atomic bomb that incinerated the Japanese city of Hiroshima at the close of World War II contained about 60 kilograms of chain-reacting uranium. When the American "Little Boy" device detonated over the doomed port, one part of the bomb's charge—a subcritical mass—was fired into the other by a relatively simple gunlike mechanism, causing the uranium 235 in the combined mass to go supercritical and explode with the force of 15 kilotons of TNT. The weapon that devastated Nagasaki a few days later used plutonium rather than uranium in its explosive charge and required much more complex technology to set it off.

Despite the production of more than 100,000 nuclear weapons by a few nations and some close calls during the succeeding 60 years, no similar nuclear destruction has occurred so far. Today, however, an additional fearful threat has arisen: that a subnational terrorist organization such as al Qaeda might acquire highly enriched uranium (HEU), build a crude gun-type detonating device and use the resulting nuclear weapon against a city. HEU is uranium in which uranium 235, the isotope capable of sustaining a nuclear chain reaction, has been concentrated to levels of 20 percent or more by weight.

The engineering required to build a gun-type atomic bomb is so basic that the physicists who designed "Little Boy" did not perform a nuclear test of the design before deployment—they had no doubt that if the "gun" fired, the weapon would explode. Experts agree, therefore, that a well-funded terrorist group could produce a workable gun-type mechanism. Indeed, some have raised credible concerns that suicidal malefactors could penetrate an HEU storage facility, construct a so-called impro-

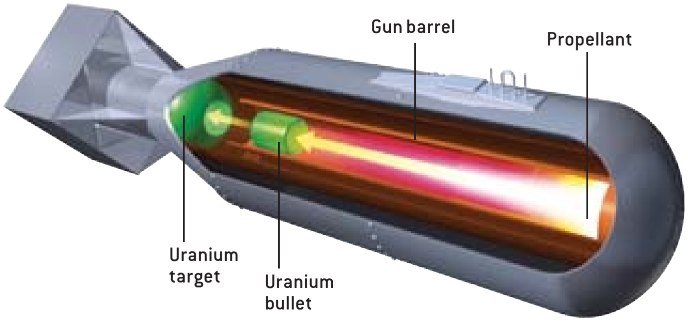
CERULEAN BLUE GLOW of Cherenkov radiation in the cooling water bath of a nuclear research reactor indicates that the system is fueled and operating. In many cases, the security measures that civilian facilities apply to protect highly enriched uranium fuel are lax, opening the possibility that the material could be stolen or otherwise acquired by terrorist groups.

ROGER RESSMEYER *Corbis*



BLUEPRINT FOR A BOMB

If terrorists obtained 60 kilograms of highly enriched uranium, they could make a nuclear explosive similar to the "Little Boy" atomic bomb that leveled Hiroshima in Japan at the end of World War II (*below*). Builders would shape a subcritical mass of the uranium into a "bullet" and place it just in front of a quantity of propellant at the far end of a closed cylinder. The remainder of the uranium (also a subcritical mass) would go at the other end of the "gun" barrel. Detonation of the propellant would send the bullet down the barrel, slamming it into the second uranium mass. The combined masses would then go supercritical and set off an explosive nuclear chain reaction.



vised nuclear device and detonate it before security guards could respond.

Although the production of HEU is beyond the means of nonstate actors, its procurement through theft or black market purchase is not: the globe is awash in around 1,800 tons of the material created during the cold war mostly by the U.S. and the Soviet Union. HEU today can be found at both civilian and military sites. We will, however, focus on that at civilian facilities in, or intended for use as, fuel for research nuclear reactors. We fret especially about civilian HEU because it is less securely guarded than military stores. (Uranium fuel for generating electricity at nuclear power plants is typically only slightly enriched—to 3 to 5 percent uranium 235 by weight.)

More than 50 tons of HEU are in civilian use, dispersed around the globe to support about 140 reactors employed to conduct scientific or industrial research or to produce radioactive isotopes for medical purposes. These sites are often located in urban areas and are minimally protected by security systems and guards. Especially worrisome is Russia's HEU-fueled reactor fleet, which constitutes about one third of the world's total and has associated with it more than half of all the civilian HEU that exists.

Improving security is essential [*see box on page* 62]. But in the long run, the most effective solution to the danger posed by nuclear terrorism is to eliminate wherever possible the use of HEU and remove accumulated stocks. The recovered HEU then should be diluted with uranium 238, the much more common uranium isotope that cannot sustain a chain reaction, to produce what specialists call low-enriched uranium (LEU)—material containing less than 20 percent uranium 235—which is not usable in weapons.

That the world has HEU at so many civilian sites stems mainly from the competitive efforts of the U.S. and the Soviet Union during the "Atoms for Peace" period of the 1950s and 1960s. As the two cold war superpowers constructed hundreds of research reactors for themselves, they simultaneously supplied such facilities to about 50 other nations to gain political favor and to establish their respective reactor technologies abroad. Later, in response to demands for longer-lived nuclear fuel, export restrictions were relaxed, which resulted in most research reactors being fueled with the bomb-grade HEU that the rivals were producing in huge quantities for nuclear weapons. This very highly concentrated material is approximately 90 percent uranium 235. As of the end of 2005, some 10 metric tons of exported bomb-grade HEU still resided in countries that do not possess nuclear weapons—enough to make 150 to 200 gun-type explosive devices.

Convert Reactors

THE U.S. GOVERNMENT first began taking steps in the 1970s to prevent diversion to nuclear weapons of the research-reactor fuel it had exported during the previous two decades. Notably, in 1978 the Department of Energy launched the Reduced Enrichment for Research and Test Reactors (RERTR) program to convert American-designed reactors so that they could run on LEU-based fuel. By the end of 2005, the effort had retrofitted 41 units. Together these

Overview/*Securing Civilian Uranium 235*

- Terrorists who acquired less than 100 kilograms of highly enriched uranium (HEU) could build and detonate a rudimentary but effective atomic bomb relatively easily. HEU is also attractive for states that seek to develop nuclear weapons secretly, without having to test them.
- Unfortunately, large quantities of HEU are stored in nuclear research facilities worldwide—especially in Russia, often under minimal security.
- The U.S. and its allies have established programs to bolster security measures, convert reactors to use low-enriched uranium (which is useless for weapons) and retrieve HEU from research-reactor sites around the world. Dangerous gaps remain, however.
- High-level governmental attention plus a comparatively small additional monetary investment could go a long way toward solving the problem for good.

SLIM FILMS

converted facilities had received shipments of approximately 250 kilograms of fresh bomb-grade HEU from the U.S. each year.

The replacement of the HEU fuel used in 42 additional reactors is now under way or planned. Unfortunately, it will not be possible to convert to LEU fuel about 10 high-powered research reactors until new LEU fuel types with the necessary performance can be developed. These high-powered reactors, which today burn about 400 kilograms of HEU fuel every year, typically feature compact cores designed to maximize the flow of neutrons for neutron-scattering experiments or materials tests requiring high irradiation levels. Current LEU-based fuel does not perform adequately within compact reactor cores that were originally designed for HEU.

To minimize the impact of the conversion on the high-power reactor designs, researchers in the RERTR program need to make LEU fuel with the same geometry and fuel life as the HEU fuel it is to replace. The job is a major engineering challenge, however. Because about four uranium 238 atoms accompany every uranium 235 atom in the LEU, fuel-element designers need to increase the amount of uranium in the LEU-based fuel elements by about five times without increasing their dimensions. After years of work, the small program to develop LEU fuel appears to be close to mastering fabrication techniques for a promising new generation of high-density fuels.

Retrieve Weaponizable Fuel

IN THE 1990S the U.S. began to cooperate with Russia on securing and eliminating HEU stocks. This effort was spurred by thefts of fresh, unburned HEU fuel in Russia and other countries of the former Soviet Union. The robberies were usually reported by the authorities only after the material was recovered. No one outside Russia—and perhaps no one inside—knows how much may have been stolen.

To limit the amount of civilian HEU in Russia accessible for unauthorized removal, the U.S. established in 1999 a Material Consolidation and Conversion Program to acquire and blend down initially about 17 tons of surplus Russian civilian HEU. By the end of 2005 about seven tons had been diluted to 20 percent uranium 235 levels.

Another effort focuses on "spent" HEU reactor fuel. Even though about half the uranium 235 has been consumed by the nuclear fission chain reaction inside reactor cores by the time the used fuel is removed, uranium 235 still makes up about 80 percent of the remaining uranium, the same concentration as the atomic charge in the Hiroshima bomb.

For several years after spent fuel is extracted from a reactor, it is "self-protecting" from theft—that is, it is so radioactive that it would surely kill within a matter of hours anyone who tried to handle it. Nuclear workers manipulate

What Nuclear Terrorists Would Need

To make nuclear weapons, terrorists would first have to buy or steal a supply of highly enriched uranium. In nature, uranium consists mainly of the uranium 238 isotope, which does not sustain a fission chain reaction when it absorbs a neutron, and a very low concentration (about 0.7 percent) of the chain-reacting isotope uranium 235. The two isotopes differ in weight by about 1 percent. Engineers can exploit this fact to separate them and concentrate, or enrich, the uranium 235. Terrorists cannot perform these operations themselves, however, because all known techniques are too difficult, time-consuming and costly.

In a mass of HEU that is just barely critical, on average one of the two to three neutrons released by the fission of a uranium 235 nucleus will go on to cause another nucleus to fission. Most of the rest of the neutrons escape through the surface of the mass, so no explosion results. To make a gun-type bomb feasible, builders need about two critical masses of highly enriched uranium so that one fission would on average cause more than one fission, thus generating an exponentially growing explosive chain reaction such as the one that released the energy of the Hiroshima bomb in a millionth of a second.

Less than one critical mass is sufficient to produce a Nagasaki-type implosion weapon. In that design the mass of plutonium was driven to supercriticality by compressing it with specially shaped external explosive charges. This implosion reduced the spaces between the nuclei through which the neutrons could escape from the mass without causing fissions.

Weapons-grade uranium contains 90 percent or more of chain-reacting, or fissile, uranium 235, but experts have advised the International Atomic Energy Agency that all highly enriched uranium (HEU)—any uranium with a uranium 235 fraction above 20 percent—must be considered "direct-use material"—that is, usable in nuclear weapons. Below 20 percent, the critical mass becomes too large to fit in a reasonably sized device. For example, to produce a critical mass using 93-percent-enriched uranium surrounded by a five-centimeter-thick beryllium neutron reflector requires about 22 kilograms, whereas it takes about 400 kilograms using 20-percent-enriched uranium. *—A.G. and F.N.v.H.*

EASY-TO-HANDLE DISKS, each containing a small amount of weapons-grade uranium, are used in one Russian critical facility in the tens of thousands. Many such disks would be required to produce an atomic bomb, but their pocketability makes guarding them against pilferage a security nightmare.

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such material only by remote means while protected by heavy shielding. The intensity of the radiation danger lessens with time, however. After about 25 years, it would take about five hours for an unshielded person working a meter from a typical five-kilogram research-reactor fuel element to collect a radiation dose that would be lethal to about half of exposed individuals. At this level, say experts advising the International Atomic Energy Agency (IAEA), the fuel can no longer be considered self-protecting.

Growing Urgency

TO COPE WITH the danger of spent HEU fuel around the world that is becoming less and less self-protecting, in 1996 the U.S. government invited foreign countries that had received American HEU fuel to ship back two common types of spent fuel. Six years later the U.S. joined with Russia and the IAEA in an effort to return fresh and spent HEU fuel to Russia. Progress has thus far been modest, though. Spent fuel that originally contained about one ton of American HEU has been repatriated so far—leaving about 10 tons still overseas. One tenth of a ton of fresh HEU fuel has been sent back to Russia, leaving an estimated two tons of HEU in fresh and spent fuel of Russian origin stored in other countries. The spent research-reactor fuel that has been shipped back to the U.S. is currently being stored at the DOE facilities in South Carolina and Idaho. Russia separates out the HEU in its spent fuel and then blends it down to make fresh low-enriched fuel for nuclear power plants.

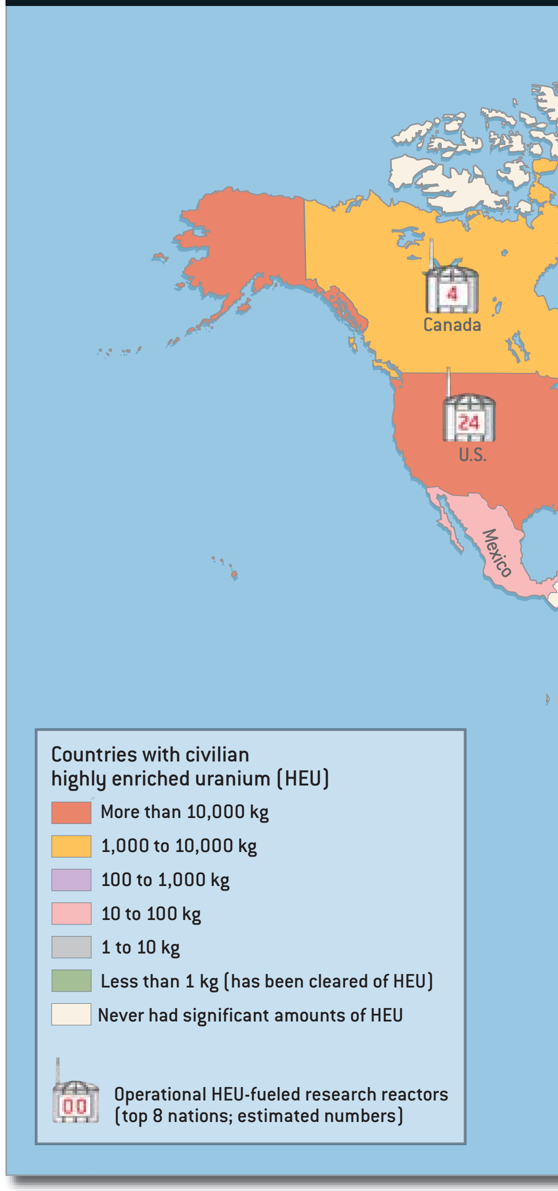
After the events of September 11, 2001, some nongovernmental organizations and members of the U.S. Congress intensified their pressure on the DOE to step up its attempts to secure civilian HEU stocks worldwide. Former Los Alamos National Laboratory weapons designer Theodore B. Taylor had warned about the danger of nuclear terrorism as early as the 1970s, but the September 11 tragedy greatly enhanced the credibility of his call for action, and demands for a "global cleanout" of nonmilitary HEU grew. In response, the DOE established a Global Threat Reduction Initiative to expand and accelerate some of the programs described above. Current targets aim to repatriate all unirradiated and spent HEU fuel of Russian origin by the end of 2006 and 2010, respectively, and all spent HEU fuel of U.S. origin by 2019. The plan also envisions that all U.S. civilian research reactors will be converted to LEU fuel by 2014.

Some elements of the HEU clean-out effort thus grew more active, but even a funding increase of more than 25 percent in fiscal year 2005 over the previous year (to about $70 million) left the program diminutive compared with multibillion-dollar programs established to deploy a missile defense system and enhance homeland security capabilities. Perversely, the low cost of the crucial HEU elimination project may partly explain why it has had no high-level advocate in any presidential administration and only a few committed supporters in Congress. Officials such as the secretary of energy and the chairs of key congressional appropriations subcommittees spend most of their time battling over big-budget programs.

In Russia, the situation is even worse. The government there appears relatively unconcerned about the danger that terrorists could acquire nuclear-explosive material. It has yet to commit to converting its research reactors to LEU fuel. Unfortunately, President George W. Bush recently backed off from pressing Russia to act. At a February 2005 summit meeting, he and Russian leader Vladimir Putin agreed to limit U.S.-Russian cooperative HEU clean-out efforts to "third countries." Putin's administration has grown increasingly resistant to programs mandating visits by foreigners to Russian nuclear facilities, particularly if those initiatives do not bring large sums of money into Russia.

The HEU clean-out projects that are still active in Russia are therefore em-

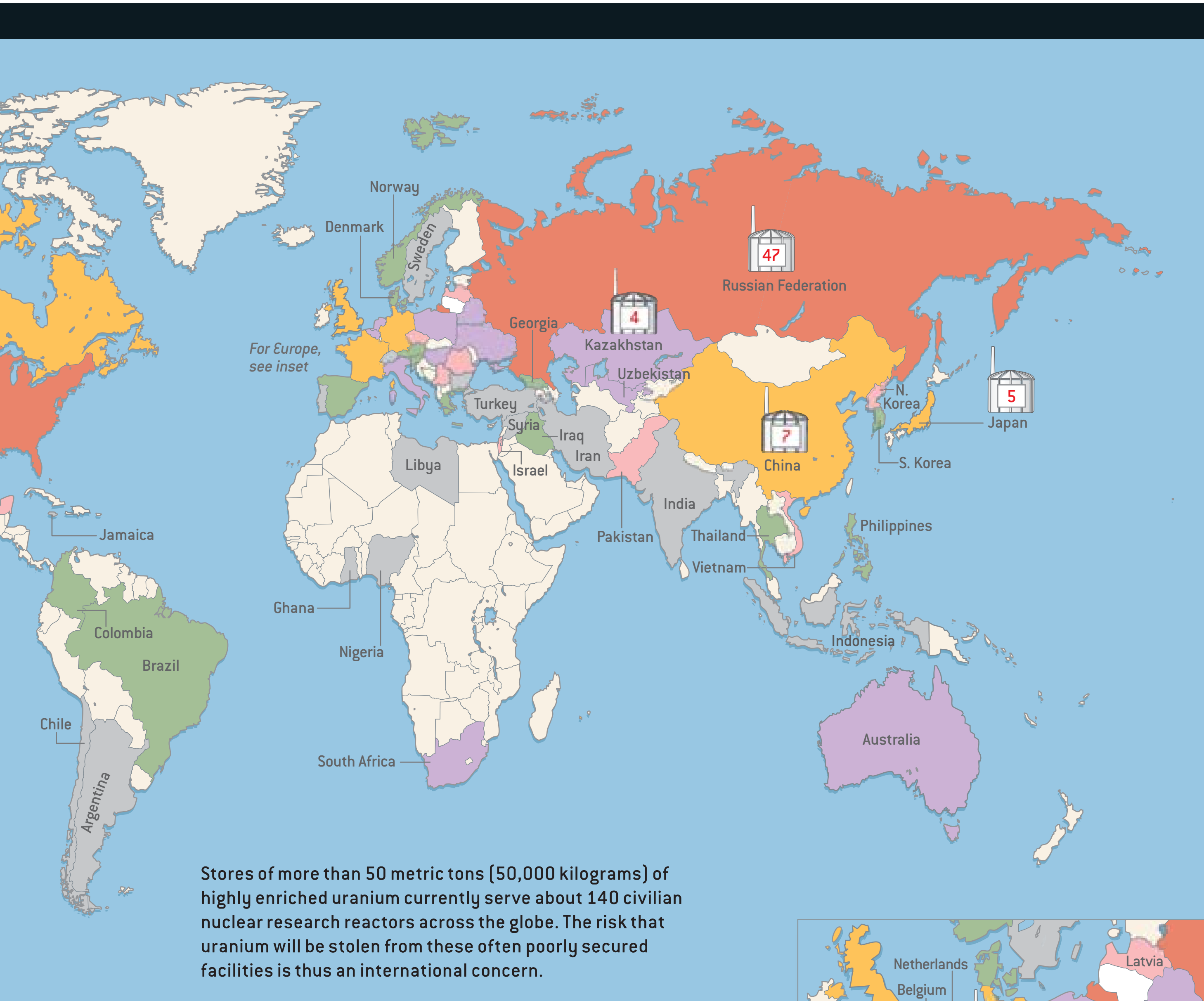
WHERE TROUBLE LIES



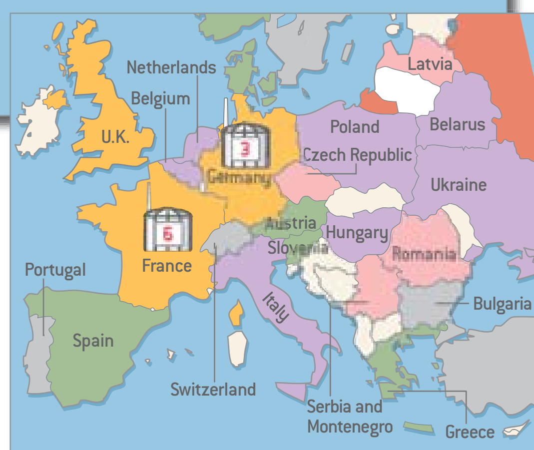
LUCY READING-IKKANDA

THE AUTHORS

ALEXANDER GLASER and *FRANK N. VON HIPPEL* are colleagues in the Program on Science and Global Security at Princeton University. Glaser, a member of the research staff, recently received his doctorate in physics from Darmstadt University of Technology in Germany, where he studied the technical barriers to research-reactor conversion. Von Hippel, a theoretical nuclear physicist by training, co-directs the program and is professor of public and international affairs. While assistant director for national security in the White House Office of Science and Technology Policy in 1993 and 1994, von Hippel helped launch American efforts to improve the security of nuclear materials in the former Soviet Union. Both work with the newly established International Panel on Fissile Materials, which is attempting to end the use of highly enriched uranium and plutonium.



Stores of more than 50 metric tons (50,000 kilograms) of highly enriched uranium currently serve about 140 civilian nuclear research reactors across the globe. The risk that uranium will be stolen from these often poorly secured facilities is thus an international concern.



ploying a "bottom-up" approach. Their representatives negotiate on a local level directly with Russian nuclear institutes one by one, leaving the institutes to obtain permission from their government. Thankfully, a million-dollar effort that seems inconsequential to the Russian government can still be very welcome to a cash-strapped nuclear institute, so several of these projects are ongoing.

Neglected HEU Sources

CURRENT EFFORTS at HEU fuel conversion and recovery address primarily HEU-powered research reactors that require refueling. They largely ignore critical assemblies and pulsed reactors, two other classes of research reactors with cores that collectively contain huge quantities of the dangerous material.

A critical assembly is a physical mockup of a new reactor core that tests whether a core design will indeed sustain a fission chain reaction, or go critical, as the engineers intended. Because these assemblies are typically limited to generating only about 100 watts of heat, they do not require cooling systems, and engineers can construct them simply by stacking up fuel and other materials.

One of us (von Hippel) first encountered such an assembly in 1994, when, as a White House official, he toured the Kurchatov Institute, an atomic energy research center in Moscow, with American nuclear materials security and accounting experts. There, in an unguard-

Halting the Theft of Nuclear Materials

By Leslie G. Fishbone

While working to eliminate highly enriched uranium (HEU) stores to thwart the building of nuclear weapons by terrorist groups, countries need to better secure the civilian research reactors that use this fuel. One approach being carried out by a collaboration of U.S. and Russian experts on Russian sites exemplifies the kinds of steps that can be taken and the problems such programs encounter.

The need for enhanced security became clear in 1992, when an engineer at a nuclear facility near Moscow stole about 1.5 kilograms of highly enriched uranium (HEU) in many small bits over several months. He hoped to sell it for profit. Fortunately, the culprit was apprehended before the uranium could be transferred to a rogue state or terrorists. The theft could have been much worse, of course. Only about 25 kilograms of uranium is required to construct some types of nuclear-explosive devices, according to estimates by the International Atomic Energy Agency.

Far from being an anomaly, the pilfering incident reflected a much wider state of insecurity. The collapse of the Soviet Union in 1991 left its nuclear complex susceptible to threats from both insiders and outsiders. Scientists, engineers and guards went unpaid for months at a time, and the system's management structure deteriorated, leading to great concern about the potential for thefts of nuclear material. The leaders of Russia, the U.S. and other countries understood the risks that unprotected materials posed and established cooperative programs to mitigate those risks.

The Material Protection Control and Accounting (MPC&A) Program, established in 1993, is one such effort. As part of the program, the U.S. Department of Energy's national laboratories work with Russian Federation nuclear organizations. Sites undergoing upgrades include civilian research laboratories, nuclear reactor fuel-cycle plants, research and production facilities for military nuclear materials, and nuclear weapons storage complexes. U.S. personnel advise and facilitate the work of Russian experts, but Russians implement the upgrades, which may encompass construction of facilities, acquisition of equipment and modification of procedures. Americans and Russians also collaborate to improve nuclear materials regulations, standards, training and accounting practices.

In some instances, rapid partial fixes are implemented until more comprehensive changes can be instituted. For example, operators might initially replace a door with a reinforced entryway featuring a sophisticated lock. Later they could install a closed-circuit television system for surveillance and threat assessment. For materials control, managers might immediately introduce a rule that all work with nuclear material must involve two people operating in tandem. Afterward technicians could put in an automated access-control system that requires special identification cards, passwords and biometric verification. For materials accounting, a quick upgrade might include scheduling regular manual inventories of nuclear materials containers that are confirmed by tamper-indicating seals. A more comprehensive measure would be the introduction of computerized measurement stations that assay (via the gamma rays issuing from the containers) the enrichment levels of nuclear materials inside. The results would be automatically entered into a computerized database that would flag anomalies.

The dozen years of Russian-U.S. cooperation in this program have yielded considerable progress. Security upgrades have been completed at 41 of 51 identified nuclear materials sites in Russia and other countries of the former Soviet Union, including weapons complexes, civilian facilities (the focus of the main article), and naval fuel storage depots. Of the 10 that remain, upgrade operations continue at eight. There is no agreement to work at the other two locations, which are highly sensitive Russian facilities. Meanwhile upgrade efforts under the MPC&A program are ongoing at warhead storage and strategic rocket sites in the former Soviet Union.

Long-term sustainability is the main challenge for the future. During the next few years, U.S. support for the program is expected to shrink, leaving the Russians to shoulder the burden alone. Although the Russian government conducts its own independent MPC&A work, equipment and procedures at many sites would soon decline if the cooperative program were to end. Maintaining the MPC&A Program is crucial to our security. Quite simply, the consequences of a significant failure to safeguard HEU could be catastrophic.

Leslie G. Fishbone works in the Nonproliferation and National Security Department at Brookhaven National Laboratory and has served in the MPC&A Program for more than a decade.

ed building, they were shown 70 kilograms of almost pure weapons-grade uranium disks stored in what looked like a high school locker. The uranium 235 was intended for a critical mockup of a space reactor. That visit led to the first U.S.-financed upgrade of the security of a Russian nuclear facility. More recently, the Kurchatov Institute and the DOE have begun discussions on a joint project that would "defuel" many of the institute's HEU-powered critical facilities.

Another such site is a critical facility at Russia's Institute of Physics and Power Engineering (IPPE) in Obninsk. This critical facility may possess the largest HEU inventory of any research-reactor site in the world: 8.7 tons, mostly in tens of thousands of thin aluminum- and stainless-steel-clad disks about two inches in diameter [*see box on page 59*]. Operators pile the disks in columns that are interleaved with other disks containing depleted uranium to simulate various average fuel-enrichment levels. Because these items emit only low levels of radiation, technicians can stack them by hand. Ensuring that no one walks out with any disks constitutes a security nightmare. We recently conducted an analysis that appears to have convinced the facility director that the laboratory does not need its weapons-grade uranium. Officials at the DOE are interested in establishing a joint project to dispose of this material.

The other underappreciated users of HEU fuel—pulsed reactors—typically

SECURITY MEASURES at many nuclear research reactor sites in the former Soviet Union do not do enough to protect highly enriched uranium from theft. American and Russian personnel are collaborating to beef up those crucial safeguards. Inspectors have found that the fencing, gates and other forms of perimeter security at some sensitive locations were often inadequate and even in an advanced state of disrepair (*top*). Since such facilities underwent security upgrades, barrier systems such as this "clear zone" around a building have presented much tougher obstacles to intruders (*bottom*).

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operate at very high power levels for periods of milliseconds or less. Weapons laboratories generally employ pulsed reactors to evaluate the responses of materials and instruments to intense but short bursts of neutrons, such as those generated by nuclear explosions. These systems pose a similar security problem to critical assemblies because their fuel, too, is only slightly radioactive. A pulsed reactor at the All-Russian Scientific Research Institute of Experimental Physics, Russia's first nuclear weapons design laboratory, located about 400 kilometers east of Moscow, contains 0.8 ton of HEU—enough for 15 Hiroshima bombs. After hearing a talk by one of us (von Hippel) about the dangers of HEU, researchers at the institute proposed to study the feasibility of converting the reactor to LEU.

Although more than 70 HEU-fueled critical assemblies and pulsed reactors exist worldwide—over half in Russia—only a few are needed for research today. Most were built in the 1960s and 1970s and are now technically obsolete. Much of their mission can be accomplished with desktop-computer simulations that calculate the progress of neutron chain reactions occurring in detailed three-dimensional reactor models. Engineers can usually confirm the validity of these mathematical simulations by checking them against the archived results of past criticality experiments. A few multipurpose HEU-fueled critical facilities may still be required to fill in gaps in previous trials, however. Engineers could convert to low-enriched fuel the few pulsed reactors that may still be needed.

More generally, one IAEA specialist has estimated that more than 85 percent of the world's aging research-reactor fleet could be decommissioned. He observed that the services they provide could be better satisfied by a small number of regional neutron sources using the latest technology. To be attractive to the researchers who use reactors, a decommissioning program could invest simultaneously in strengthening the capabilities of the remaining research-reactor centers. European nations and Japan could join with the U.S. in such an endeavor. In fact, the closings could provide a source of funding for the institutes owning reactors with large inventories of lightly irradiated HEU: these stores would bring in about $20 million per ton of HEU after it was blended down to the safe LEU used to fuel nuclear power plants.

Toward a Solution

THE EFFORT TO CONVERT HEU-fueled reactors has already dragged on for more than a quarter of a century. That the use of HEU continues has little to do with technical reasons. This failure has resulted largely from a dearth of sufficient high-level governmental support. Resistance on the part of reactor operators fearing relicensing or shutdown has also caused holdups.

Despite current concerns over nuclear terrorism, most segments of the HEU clean-out program are still proceeding much too slowly. Governments need to increase funding to accelerate the conversion of reactors for which substitute LEU fuel is available and to ensure that practical replacement fuel elements are developed with which to convert the remaining ones. Further, the program must be broadened to include all HEU-fueled critical assemblies, pulsed reactors and a few other civilian users of HEU fuel, such as Russia's nuclear-powered icebreakers.

If the U.S. and its allies were to take seriously the challenge of preventing nuclear terrorism, civilian HEU could be eliminated from the world in five to eight years. Continued delay in completing this task only extends the window of opportunity for would-be nuclear terrorists. SA

MORE TO EXPLORE

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Protecting New Orl

eans

Hurricanes Katrina and Rita devastated the Gulf Coast. The storm season starts again this June—and every June. Can coastal communities ever be safeguarded?

By Mark Fischetti

Immediately after Hurricane Katrina pummeled New Orleans last August, President George W. Bush and the U.S. Department of Homeland Security declared that no one could have predicted such devastation. Yet scientists, engineers and Louisiana state politicians had warned for years that a Category 4 or 5 storm crossing the Gulf of Mexico from a certain direction would drown the region. In 1998 computer models at Louisiana State University simulated such a terrible inundation. That same year the state proposed a $14-billion plan to restore the delta's natural wetlands—which, by absorbing water, can help protect inland areas from sea surges. But Congress turned it down.

What is more, engineering firms, as well as the U.S. Army Corps of Engineers, which is largely responsible for flood protection, had proposed constructing higher earthen levees as well as huge gates that could have prevented storm surges from pouring into inner-city canals and bursting their concrete flood walls. Indeed, documents show that various gates had been recommended as far back as 1968 and in each decade since.

None of these designs has ever been funded. The reason, for the most part, is turf battles among the Corps, local and state politicians, and Congress. In the meantime, countries such as the Netherlands and the U.K. have erected effective surge barriers that the U.S. has ignored. In Katrina's wake, the blueprints for all these structures are rapidly being dusted off, augmented and integrated into several grand plans by L.S.U., big engineering companies, and the Corps that could safeguard New Orleans and southeastern Louisiana. Similar measures could save populated coastal communities around the Gulf, the U.S. and the globe.

Poster Child

THE MISSISSIPPI RIVER DELTA is not alone in being endangered. Deltas worldwide are in trouble because human development is causing the land to sink. The soft delta earth compacts naturally, but annual river floods top-coat the slumping ground with new sediment. Yet man-made levees built to prevent floods in many of these regions also cut off the sediment supply. At the same time, underground extraction of oil, natural gas and freshwater deflates the land's support structure. As the surface subsides, saltwater from the ocean streams in, poisoning the usually thick expanses of wetland mangroves, trees and grasses. Without these lush buffers, even moderate storms can push sea surges far inland.

The earth's oceans are also rising, compounding the problem. At current rates, sea level will be one to three feet higher in 100 years. Low-lying cities from New York to Shanghai may have to armor themselves with walls and pumps and add revetments (waterproof masonry) to the bottom few feet of every building in town, measures already under way in Venice.

One third of the world's people live in coastal zones, particularly the deltas. Rich

HIGH WATER pours through a burst flood wall along New Orleans's 17th Street Canal.

in farmland, seafood and underground resources, these areas are also key exit and entry points for armadas of ships carrying piles of goods. Cairo, at the tip of the Nile River, is home to 16 million people. The Red River and Mekong deltas in Vietnam each support 15 million inhabitants, yet both are eroding. Shanghai has 13.5 million, the Ganges in Bangladesh, 10 million. Other threatened deltas include the Orinoco in Venezuela and the Rhine, Rhône and Po in Europe.

The Mississippi Delta, home to 2.2 million, represents the worst-case scenario. It is sinking and losing wetlands faster than almost any place on earth and faces the most hurricanes annually. The record sea surge that prompted the Netherlands and Britain to erect barriers was 15 feet; Katrina's peaked at 28 feet.

Fundamental to the trouble is that for the past century the Corps, with the blessing of Congress, leveed the Mississippi River to prevent its annual floods so that farms and industries could expand along its banks. Yet the levees have starved the region of enormous quantities of sediment, nutrients and freshwater. Natural flooding at the river's mouth had also sent volumes of sediment west and east to a string of barrier islands that cut down surges and waves, rebuilding each year what regular ocean erosion had stolen. But because the mouth is now dredged for shipping lanes, the sediment simply streams out into the deep ocean, leaving the delta—and New Orleans within it—naked against the sea.

The Corps and industry also tore up the marsh by dredging hundreds of miles of channels so pipelines could be laid. Even bigger navigation channels were dug, and wave erosion from ships turned those cuts into gashes that allow hurricane-induced surges to race into the city. Similar practices are in play at many of the world's deltas, which could well benefit from plans such as those now being considered in Louisiana.

Too Late to Be Saved?

THE 1998 PLAN for protecting the Mississippi Delta region, titled Coast 2050, and a modified scheme in 2003 known as the Louisiana Coastal Area plan (LCA), called for gates to be inserted into the river levees. The gates would open at certain times of the year to allow freshwater and sediment to wash down into the wetlands, gradually restoring them. But "a growing number of people are recognizing that Katrina and Rita changed the landscape enough that they may have made Coast 2050 and LCA obsolete," laments Len Bahr, a leader in the Louisiana Governor's Office of Coastal Activities for 15 years and an architect of Coast 2050.

Furthermore, because the storm surge entered New Orleans from Lake Pontchartrain to the north and navigation channels to the east, "those plans would not have stopped Katrina," observes Hassan S. Mashriqui, an assistant research professor at L.S.U.'s Hurricane Center who has enhanced the university's 1998 surge models. He says the models show that gates across certain channels into the city would also have been needed to divert the surge.

Those gates would have done nothing for the rest of southeastern Louisiana, however. SCIENTIFIC AMERICAN therefore asked a wide range of experts

Overview/*Flood Control*

- Levees were too small and weak to hold back Hurricane Katrina's storm surge. Much more robust systems have been proposed for all of southeastern Louisiana.
- Flood control structures already in place in the Netherlands, England and elsewhere could help protect troubled deltas worldwide and also revive vast, dying marshlands.
- Engineers must embrace greater scientific input when considering the siting and construction of barriers—input that might have mitigated the Katrina disaster.

Grand Plan

Three main protection schemes (*top map*) are being proposed by government, industry and university groups to hold back floodwaters from Category 5 hurricanes. The "inner ring" (*red*) would extend and add height and width to current levees and canal walls throughout New Orleans, meant only to withstand Category 3 storms, and connect to existing Mississippi River levees.

A "comprehensive plan" (*yellow*) would continue the line to the Mississippi state border and west beyond Morgan City to protect more communities and industry. The 440-mile levee, 35 to 40 feet high, would loosely track the Intracoastal Waterway to the west, the primary intramarsh navigation route. The path shown represents a consolidation of contours plotted independently by the Shaw Coastal engineering firm, the U.S. Army Corps of Engineers, and Hassan Mashriqui of the Louisiana State University Hurricane Center.

In each case, diversions—sluices within Mississippi River levees—would open at certain times of the year to allow freshwater, nutrients and sediment to wash down into the marshes, reviving vegetation and building up land to counteract subsidence and sea-level rise. The Bonnet Carré floodway, completed, can siphon away flood-stage river water.

Other experts prefer dikes and long chains of gates that would link the barrier islands, forming an "outer shield" similar to that in place in the Netherlands. (No one has plotted a complete course, but examples appear in pink.) Diversions would still be installed to restore wetlands, important to the environment and industry. Along with any plan, a new shipping entry point is recommended partway up the Mississippi, which would require dredged channels but shorten travel times and end dredging of the river tips; they would fill, sending sediment to the barrier islands and marshes to replace sand eroded by wave action.

In each scheme, numerous gates of different styles would be erected (*bottom*). They would stay open for shipping and for maintaining the natural mixing of freshwater and saltwater but close when needed to prevent storm surges from entering Lake Pontchartrain or navigation and drainage canals.

Inner ring
Comprehensive plan
Outer shield (sample sites)
Diversion (samples)
Gate
Existing levee
Katrina levee breach

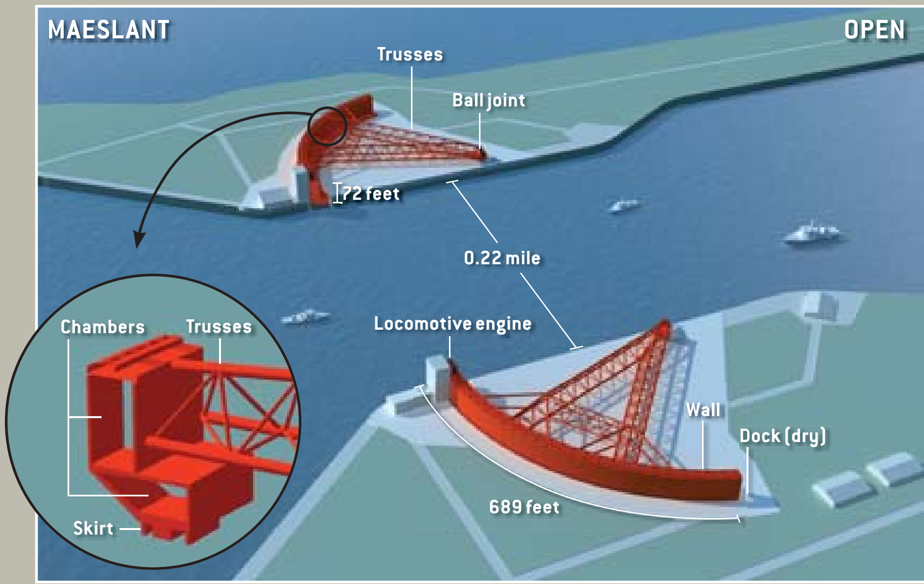
NOTE: Plots are approximate.
SOURCES: Louisiana State University, Shaw Coastal, U.S. Army Corps of Engineers, Coast 2050; satellite data available from U.S. Geological Survey at the National Center for EROS, Sioux Falls, S.D.

According to an L.S.U. plan, the so-called funnel of water that caused the largest flood-wall breach during Hurricane Katrina would be regulated, and the MRGO channel, a source of extensive wetland erosion, would be closed. Some experts propose a "safe haven"—walls underneath elevated highways that would create an unflooded refuge if problems arise.

JEN CHRISTIANSEN

Floating Gates

Floodgates around the world stop surges from pouring inland, and building ones like them could help New Orleans and other coastal cities. The Netherlands has the greatest variety. The Maeslant barrier (*right*) allows shipping on the New Waterway from the North Sea into Rotterdam's huge port but closes during storms. Each hollow barrier is stored in a dry dock, to limit corrosion and ease maintenance. For deployment, the dock is filled with water, the gate floats, and an engine turns it out. Valves then let water fill and sink the gate. After a storm, pumps empty the chambers, the barrier is floated back in, and the dock is pumped dry.



to present solutions for the region. Three strategies [*see maps on preceding page*] emerged: a tight ring around the New Orleans metropolitan area alone; a comprehensive, 440-mile levee system that would snake from the Mississippi border halfway to Texas but lie only partway to the shoreline, leaving the coast for lost; and an outer shield around the region's perimeter, such as the one in the Netherlands, which would spare every locale. The ring and comprehensive plans would inevitably leave some people "outside the wall." All three plans include gates of some kind that are not now in place.

Although each approach has its proponents, the parties agree on one thing: critics who say it is foolish to rebuild in such a vulnerable place are missing the big picture. In addition to being a cultural center, "the Gulf Coast is the economic engine that drives the country," Bahr declares. "We can't possibly abandon it." The delta produces one fifth of the country's oil, one quarter of its natural gas, and one third of its seafood. Trillions of dollars of goods and crops flow through the ports there. These activities require extensive infrastructure and tens of thousands of employees who cannot live in temporary trailers or in homes two hours away.

A New Path

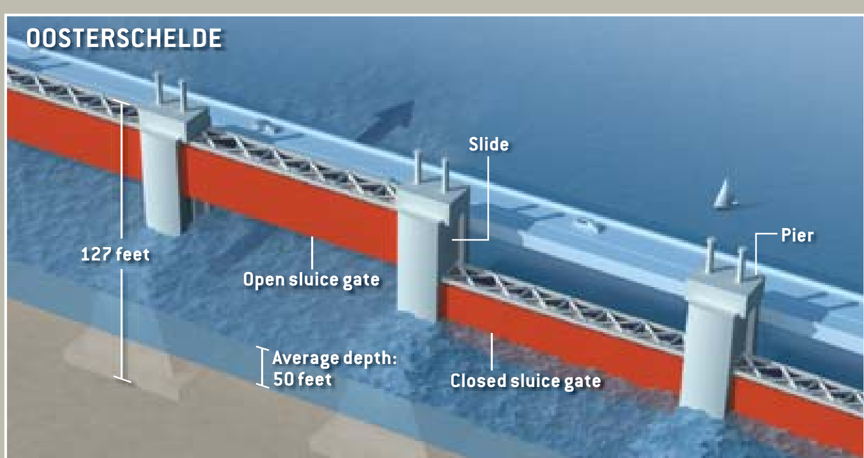
BEFORE ANY PLAN is implemented, designers should understand fully why the existing levees failed, so weaknesses can be avoided in the future. Four teams are investigating the levee and canal wall collapses in New Orleans—from the American Society of Civil Engineers, the Corps, the state of Louisiana and the National Science Foundation.

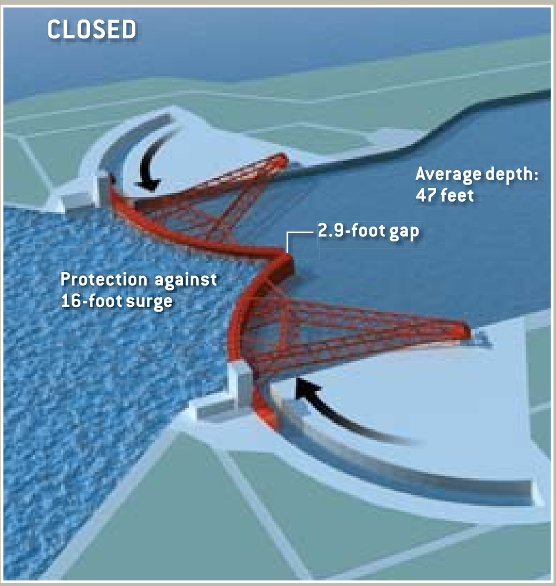
In October, Secretary of Defense Donald Rumsfeld announced that the National Academy of Sciences would review all the reports to ultimately determine why flood walls crumbled [see Working Knowledge, on page 92]. Rumsfeld said the academy would finish by June 2006. Yet hurricane season officially begins June 1, and Richard Wagonaar, a U.S. Army colonel and commander of the Corps' New Orleans district, says his goal is to restore all federal levees to their pre-Katrina level of protection (able to withstand Category 3 hurricanes) by that date. President Bush had asked Congress to appropriate $1.6 billion to repair levee damage from Katrina and in December requested another $1.5 billion to

BRYAN CHRISTIE DESIGN (*diagrams*); JEN CHRISTIANSEN (*map*)

Sluices That Slide

Long stretches of sluices link firm shorelines, barrier islands and dikes to form one part of Holland's outer shield—the Oosterschelde barrier (*right*). These floodgates could aid any of the New Orleans protection schemes. The Oosterschelde complex, 1.8 miles long, crosses three channels. When raised, the 62 steel gates between concrete piers allow for three quarters of the original tidal movement, which maintains the estuaries behind it.





OOSTERSCHELDE: SKY PICTURES; MAESLANT: RIJKSWATERSTAAT, MINISTRY OF TRANSPORT, PUBLIC WORKS AND WATER MANAGEMENT

improve city levees at Category 3 levels.

Wagonaar and others see restoration as only the first step, however. They agree that the city's protection must be raised to Category 5 levels. Congress would have to appropriate much more money for this work, whether it went to the Corps or a different contractor.

When it comes to the comprehensive plans, people become more contentious. Despite local differences, the plans outlined by Shaw Coastal (part of the Shaw Group), Mashriqui and Wagonaar follow a somewhat similar route. To the south and west, the course would link and raise existing, piecemeal levees now maintained by independent levee districts and would protect most major towns. The planners disagree, though, on who should do the work as well as on how long construction would take and what it would cost. Wagonaar estimates the Corps' plan "would take us five to 10 years to build" and that the cost "would be $25 billion to $35 billion—but remember, this is still in the concept stage."

That time frame seems unrealistic to O'Neil P. Malbrough, president of Shaw Coastal, an engineering firm that has built smaller levees and floodgates elsewhere in the country. "The Corps began building levees around New Orleans and Lake Pontchartrain in 1965, and there are still segments that are incomplete," Malbrough says. "That's inexcusable. If private enterprise were doing this, it would cost half the money and take half the time. The Corps is still building the same wall it was building then."

Wagonaar says he is not familiar with Malbrough or with Shaw's plan and notes that companies are unlikely to be involved unless Congress opens bids for the work. The Corps has had a de facto monopoly on federally funded flood protection for a century.

Residents in the hurricane danger zones hope that whoever gets the job incorporates new understanding of how Katrina and Rita ravaged New Orleans, and some worry that the Corps may not be fully responsive to external scientific information. For example, Mashriqui at L.S.U. has determined that a wide breach in the Industrial Canal, which flooded the eastern section of the city after Katrina, was caused by what is called a funnel effect. Computer simulations, and physical evidence Mashriqui obtained in October as a member of the state inspection team, show that Katrina pushed water from the east up a wide navigation channel called MRGO and simultaneously up an adjacent channel, the Intracoastal Waterway. The two wave fronts met where the inlets join and narrow into the Industrial Canal. This geometry amplified the height of the water by 20 to 40 percent, Mashriqui says. That increase raised the water pressure so high that the canal wall burst.

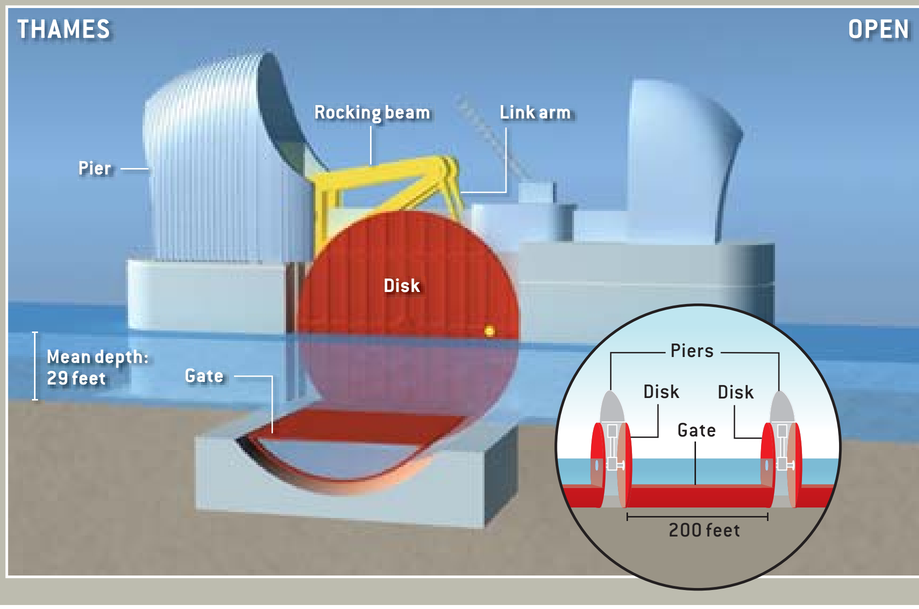
Scientists had predicted the funnel effect, and Mashriqui says a preparedness exercise run in 2004 by the Federal Emergency Management Agency based on a simulated hurricane called Pam also involved a funnel effect in that place. "The wind pushes a huge volume of water into this narrow strait, and the water just piles up," he says.

MRGO must be closed and gates must be put across the Intracoastal Waterway to protect the city, Mashriqui says. Numerous other experts speaking to the national press have concurred, noting that it supports very little ship traffic and costs a lot to maintain. But the Corps built MRGO, Mashriqui notes, "and for them to agree, they would be admitting a mistake was made in the first place."

Mashriqui is not the only one worrying about the need to avoid funnel effects. This very phenomenon was a chief reason for building the Thames Barrier in 1982, to prevent storm surges from piling up along the Thames Estuary close to London. "As the channel narrows by 50 percent, the water piles up by 100 percent," says Martin Earlam, chief engineer for the barrier at the country's Envi-

Hydraulic Disks

A 1953 storm that drowned the Netherlands also sent a 15-foot surge up the Thames Estuary, killing 300 in England. Today 10 steel gates span the river, held by piers covered by shining hoods (*photograph*). The four central gates are each 200 feet across and lie flush in the riverbed, full of water, to not obstruct shipping. A disk on each end of the gate is mounted on a shaft. To raise a gate, hydraulic rams and arms rotate it while air enters the gate and water drains. Water refills the gate when it is brought back down.



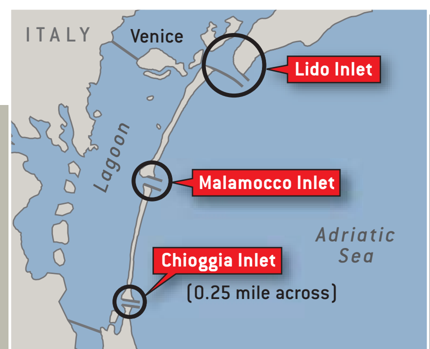
ronment Agency, which operates it. And S. Jeffress Williams, a coastal scientist with the U.S. Geological Survey who worked for 20 years in Louisiana and has studied deltas worldwide, says funnel effects "have been underappreciated."

Outer Shield

THE COMPREHENSIVE PLAN may seem more feasible than the total shield, but there are reasons to consider enclosing the significant tracts of marsh that the other plans would leave exposed to the sea. The marshes provide wintering grounds for 70 percent of the nation's migratory waterfowl, cushion ocean waves that could otherwise disturb shallow underground pipelines, and could partially absorb rising sea levels. The region could be walled in by connecting the barrier islands with dams and long stretches of gates—the option the Netherlands embraced after a horrific 1953 storm generated a 15-foot surge that killed 1,800 people and flooded 800 square miles. Virtually the entire country is delta; 26 percent of it is below sea level, bottoming out at –22 feet, lower than New Orleans. The surface is subsiding, too, accelerated by extraction of freshwater and peat, and is home to several major lakes and river outlets. Today the nation is outlined by more than 1,000 miles of dikes (levees), dunes, dams and gates—far longer than the line needed around Louisiana.

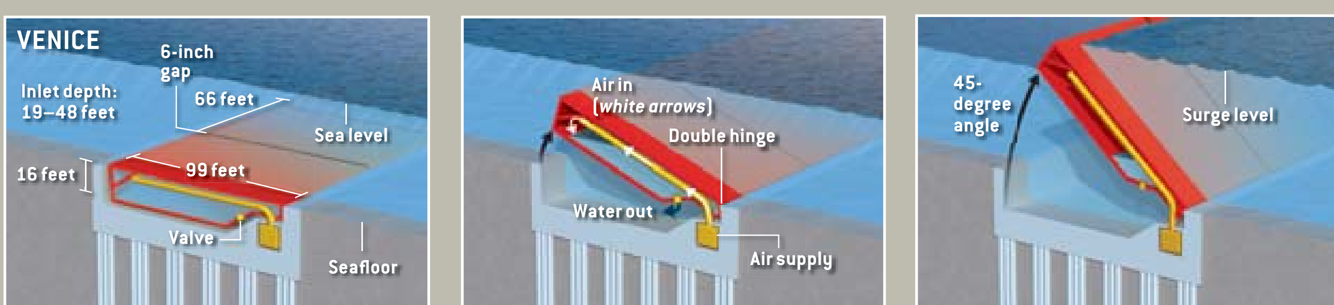
Joop Weijers, a longtime senior engineer at the Dutch Ministry of Transport, Public Works and Water Management, which oversees the Delta Works network, says a similar approach could protect Louisiana and deltas in other nations. Although the Netherlands's shield may seem grandiose, Weijers says "building the whole system right now would cost $15 billion to $16 billion." Maintenance runs about $500 million a year. But after the coast was secured, he adds, "the region got an economic boost in tourism, farming and industry."

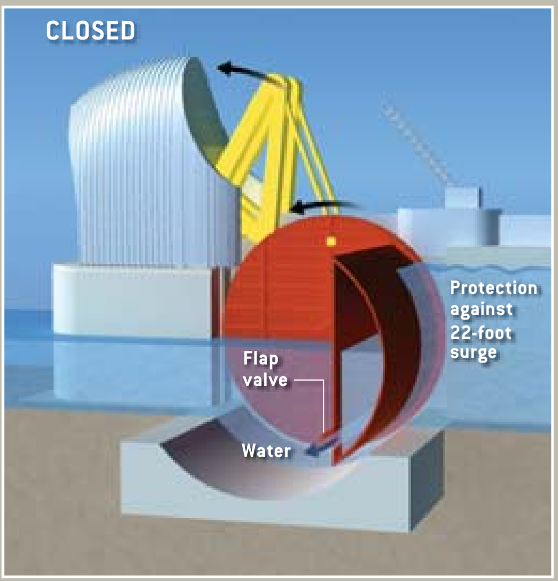
Coastal administrator Len Bahr says an outer shield is a wild idea, but given the delta's alarming deterioration, "we may need some wild new ideas." Williams of the USGS concurs: "Considering



Rising Flaps

Many low-lying coastal cities worldwide will have to fend off tidal surges and rising sea levels. In Venice, engineers are preparing sites for barriers that will close inlets when menacingly high tides approach, which now occurs three or four times a year (record surge, 6.5 feet). In each inlet, 20 or 40 hollow, steel flaps will rest in heavy concrete cradles. To raise them, air will be pumped in to push water out, and they will float up into position in less than 30 minutes (*diagrams*). An adjacent lock will permit boats to pass.





the rates of sea-level rise, land subsidence, and the increasing frequency and severity of storms, it's a legitimate option."

Take a Scientist to Lunch

PANICKED BY the devastation in 1953, the Dutch quickly set out to build solid dams across several wide estuaries to the North Sea. Those berms, however, cut off the interchange of saltwater and freshwater and altered the environment. In recent decades, Delta Works has changed direction, emphasizing man-made barriers that close only when surges are imminent. "It took us a long time to learn that we could work with nature, not just defy it," Weijers says. He advises U.S. planners to "really think it through."

Wagonaar at the Corps, Malbrough at Shaw Coastal, and Mashriqui at L.S.U. agree that certain aspects of the original Coast 2050 and LCA plans that would revive the marshes must be incorporated into any plan adopted. Diversions—large doorways inserted into the levee along the Mississippi River's banks—would supply freshwater and sediment to the wetlands. The Corps' plan includes a significant number of gates to "let water flow in and out to support the LCA objectives," Wagonaar says.

Although the Netherlands and Britain probably have much advice to offer, Malbrough says, "we don't need the Dutch to tell us how to build a levee system." The Corps apparently felt that way at one time, too; its officials made similar statements to SCIENTIFIC AMERICAN during research for a 2001 article about restoring the delta [see "More to Explore" below]. But collaboration may improve. In 2004 the Corps and Delta Works leaders signed a memo of understanding to exchange information, and in October several Dutch engineers helped the Corps analyze New Orleans's flood-wall failures.

The need to coordinate physical protection across levee districts and to incorporate coastal restoration means a clear leader is needed. The experts interviewed for this article acknowledged that political infighting in Louisiana killed smaller proposals in the past. Malbrough hopes this message may be sinking in; he was hired by various levee boards together to present the state and federal government with one coordinated plan. Both he, Mashriqui and Bahr think a federally run consortium should oversee the work. They oppose putting the Corps in charge, seeing it as too slow, too politicized by Congress, and too unwilling to entertain novel technical approaches. "I'm inclined to change horses," Mashriqui says.

He and others also strongly recommend that scientist input be sought much more extensively. "I don't care who wants to control the work," Mashriqui asserts. "But whoever it is has to listen to the data. If our models show that the funnel effect will kill people, then there is no excuse not to close the funnel."

Bahr agrees that engineers "have not so far engaged research scientists nearly enough. And we need anthropologists and social scientists to help figure out the people issues. Some parishes [counties] were virtually wiped out by Katrina. Where does it make sense, socially, to rebuild?" Williams, the USGS veteran who also worked at the Corps for 13 years, says scientists continually "put data out there, but it has no effect on its own. Politicians and planners have to take it from there."

Wagonaar, a longtime Corps member who took over the New Orleans district last July, says that in the future the Corps will better integrate outside experts: "We are generally a lot more open than we were five or six years ago, especially with regard to environmental issues. But we can't study this situation forever either. Someone will have to make a decision." SA

MORE TO EXPLORE

Drowning New Orleans. Mark Fischetti in *Scientific American*, Vol. 285, No. 4, pages 76–85; October 2001.

Preliminary Report on the Performance of the New Orleans Levee Systems in Hurricane Katrina on August 29, 2005. R. B. Seed et al., Report No. UCB/CITRIS-05/01, University of California, Berkeley, and American Society of Civil Engineers, November 17, 2005. Available at **www.asce.org/files/pdf/katrina/teamdatareport1121.pdf**

Drawing Louisiana's New Map: Addressing Land Loss in Coastal Louisiana. National Research Council. National Academies Press (in press, scheduled for February 2006).

BRYAN CHRISTIE DESIGN (*diagrams*); JEN CHRISTIANSEN (*maps*); THAMES: SKYSCAN

Miniaturized POWER

With nanobatteries, power sources finally shrink with the rest of electronics

By Charles Q. Choi

The transistor, dating from 1947, has shrunk from a kludgy, half-inch-high contraption to a device whose components boast dimensions a few hundreds of atoms in length. Batteries, on the other hand, have improved how much power they deliver at roughly one fiftieth of that pace.

Bell Laboratories, which built the first transistor, has now become involved with the reinvention of the battery. The goal is to apply the techniques used for manufacturing transistors to mass-produce a battery that can be built in with the other circuitry on a chip. The device, called a nanobattery, shrinks features of the electrodes to the nanometer scale.

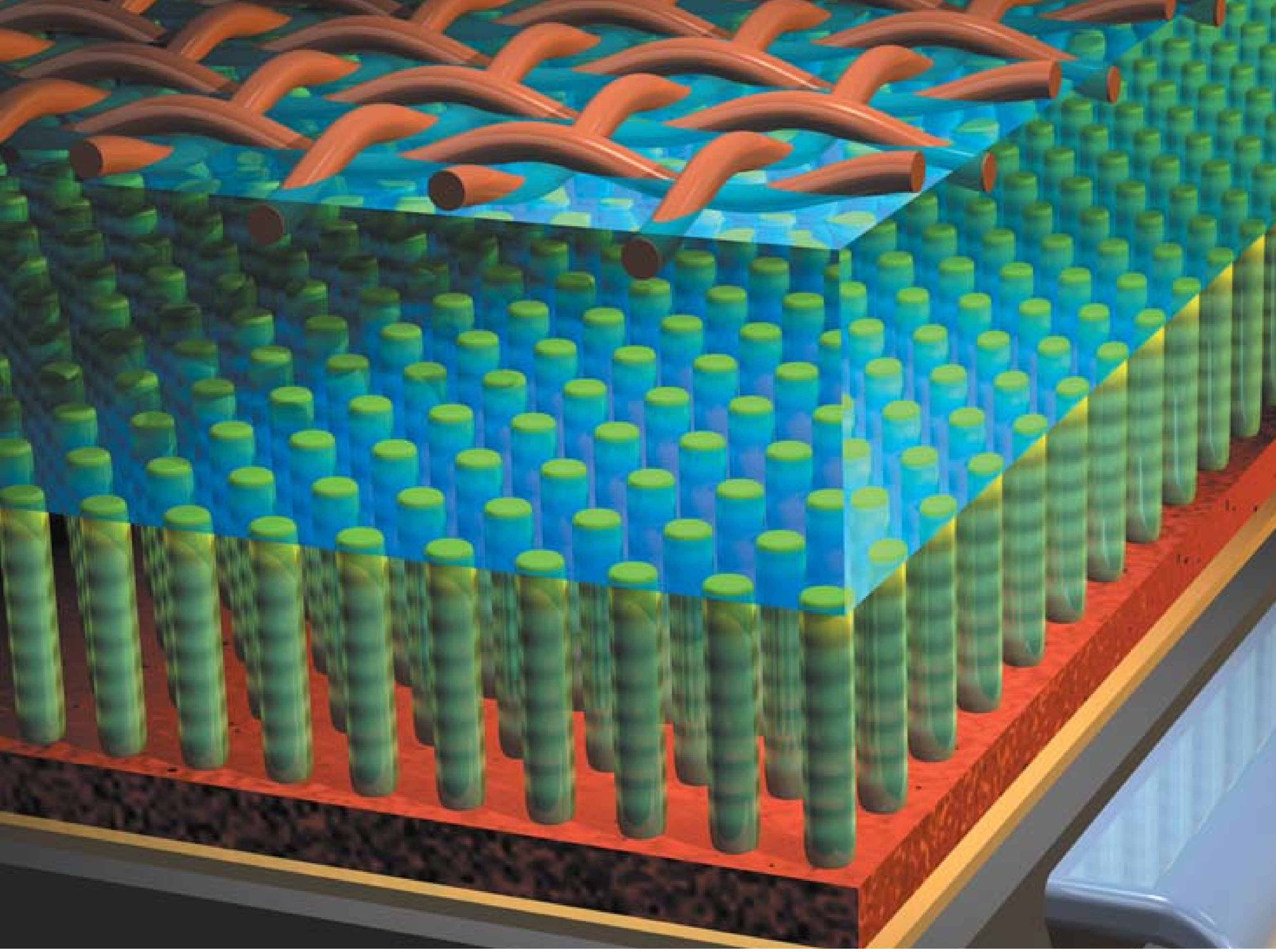
The design of the nanobattery enables it to lie dormant for at least 15 years, perhaps as a power source for a sensor that monitors radioactivity or one that tracks the buildup of toxic chemicals. It is then capable of waking up and immediately providing a burst of high energy. The concept could also lead to the first batteries that can clean up after themselves, by neutralizing the brew of toxic chemicals inside.

Growing Nanograss

THE GENESIS of the nanobattery springs from an earlier Bell Labs foray into nanotechnology. In the fall of 2002 Lucent Technologies, Bell Labs' corporate parent, was preparing to launch the New Jersey Nanotechnology Consortium with the state government and the New Jersey Institute of Technology. The idea was to make the company's research, development and prototyping services accessible to industry, academic and government nanotechnologists. David Bishop, vice president of nanotechnology research at Bell Labs, had begun seminars for company scientists to share ideas on how their research might find novel applications for consortium members to develop further.

One Bell Labs presenter, Tom Krupenkin, had worked on liquid microlenses, the kind now often found in camera phones. These lenses consist of droplets that can alter their focal properties by changing shape in response to a voltage applied to a surface with which they are in contact. In response to the voltage, these so-called electrowetting surfaces can turn from superhydrophobic to hydrophilic.

Superhydrophobicity is the property that helps rain roll off duck feathers and lotus leaves. Surface tension makes drops of liquid want to bead up, but the solid they rest on can exert attractive forces that cause them to spread. On hydrophilic substances such as glass, water stretches out. But on superhydrophobic materials, droplets ball up completely,



SLIM FILMS

NANOGRASS consists of 300 nanometer-wide pillars, which resemble grass blades. A radically new battery concept incorporated these structures, which kept a liquid electrolyte on top of the nanograss until the power source was ready to be activated.

essentially not interacting with those surfaces at all.

Given that droplet behavior on a superhydrophobic surface, Krupenkin reasoned, electrowetting could help control a chemical reaction. He sketched out a concept that involved rows of superhydrophobic nanometer-wide pillars that can exhibit electrowetting. Under a microscope, these resemble a field of evenly cut "nanograss." Such nanograss can be made with standard microchip industry techniques developed over the decades to work on silicon. Applying a voltage to the liquid, scientists could create a reaction that causes the pillars to become hydrophilic and draw the droplets down to penetrate the interstices among the nanopillars. The liquid could then react with any compound that rests at the bottom. It struck Krupenkin that the liquid could be used to create power in a nanobattery.

Batteries are essentially chemical reactors. A disposable battery consists of two electrodes, an anode and a cathode, bathed in an electrolyte solution. The compounds that make up both electrodes react with each other via the electrolyte to generate electrons. The problem, however, is that these electrochemical reactions happen even when batteries are not connected to devices. The average battery loses as much as 7 to 10 percent of its power a year when not in use.

So-called reserve batteries employ physical barriers to keep the electrolyte separate from the electrodes until the batteries are activated; the especially aggressive electrochemical reactions that result provide bursts of high energy. The mechanical challenge of keeping the electrolyte away from the electrodes translates into large and clunky batteries. Consequently, they mainly find use in emergency situations, such as in hospital intensive care units or operating rooms, and in military applications, such as night-vision goggles or laser illumination.

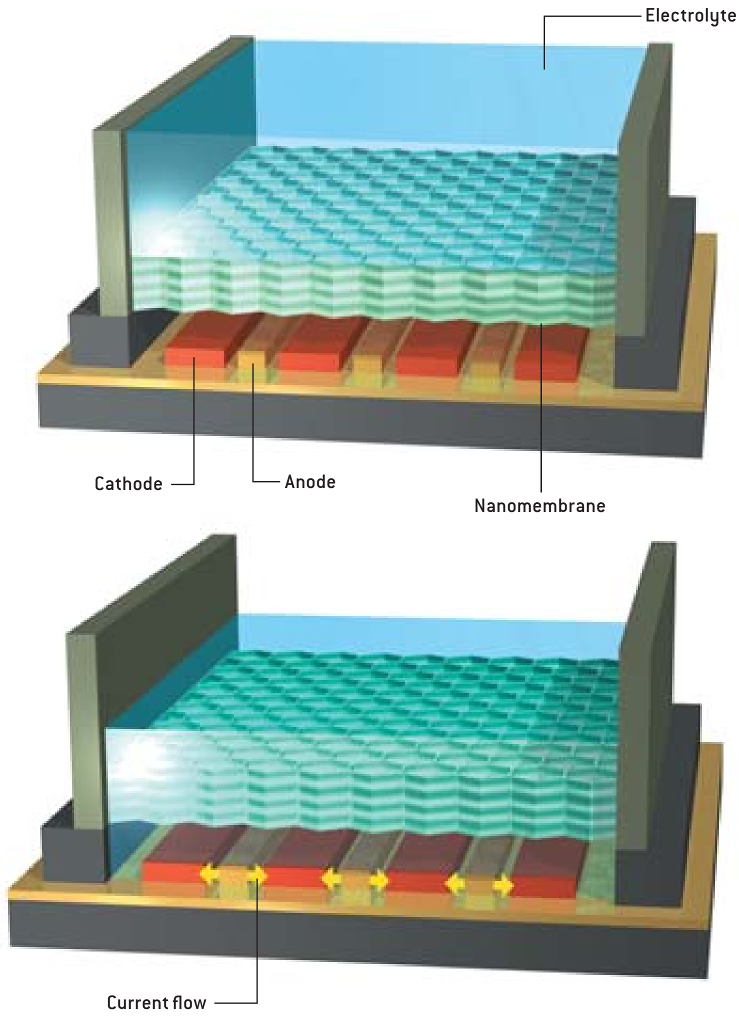
The advent of nanograss offered the possibility of making reserve batteries far easier to miniaturize. Moreover, instead of reacting all the chemicals at once, researchers can design their battery to activate only fractions of the field of nanograss at one time, Krupenkin explains.

Bell Labs started to shop the nanograss concept around. "Lucent is not a battery company but would like to revolutionize batteries," Bishop says. At a seminar in late 2003, a company called mPhase heard a presentation from Lucent about a nanotechnology-based bat-

DESIGN FOR A NANOBATTERY

A battery prototype nanomembrane built by mPhase and Bell Labs keeps electrolyte separated from the negative and positive electrodes (the cathodes and the anodes), which gives the battery a longer life. In the initial, unactivated state (*top*), the zinc anodes and manganese dioxide cathodes lie in patches on the floor of the battery, physically separate from one another. Above them rests a porous honeycomb membrane, made of silicon and covered with a layer of silicon dioxide and a fluorocarbon polymer. Atop this barrier is the zinc chloride electrolyte solution.

In the activated state (*bottom*), the electrolyte has penetrated the honeycomb to immerse both the anode and cathode patches. Once the anodes and cathodes are linked by the electrolyte, they react with one another to generate electricity.



tery. "We left the room and said, 'Holy mackerel, that was spectacular,'" remembers Steve Simon, mPhase's executive vice president of engineering, research and development. At the time, mPhase was primarily a home broadband and video DSL components firm that was spun out from Norwalk, Conn.–based Microphase, a microwave electronics company for the military, aerospace and telecommunications industries.

As telecommunications hardware increasingly became a commodity market, mPhase chief executive officer Ron Durando sought to reinvent the company as a nanotechnology provider. He specifically wanted a device that would not take too long to develop, would not have medical uses that could tie it up with the red tape of clinical trials, and could serve a military market that supported the premium prices nanotechnology devices often command in early production runs. "The battery fit all three," Simon explains.

In March 2004 mPhase sealed a joint development agreement to commercialize the nanobattery. While mPhase investigates what potential customers want from the battery to create profitable devices, Lucent provides the license for the technology in return for royalties, the benefits of a $450-million clean room and access to scientists with decades of experience in silicon manufacturing.

Getting It to Work

BY SEPTEMBER 2004 the scientists had an operational model in their laboratory that could generate current. To get its prototype, the team had to create silicon pillars each roughly 300 nanometers wide and spaced about two microns apart. For power generation, the researchers employed compounds used in common alkaline batteries, with zinc as the anode material and manganese dioxide as the cathode. The silicon floor the pillars rest on is coated with zinc, whereas the pillars themselves are covered with silicon dioxide, which allows the investigators to control the voltage of the device, and the nanopillar tips are coated with a Teflon-like fluorocarbon layer, which exhibits the electrowetting behavior.

"Things that are simple conceptually are hard to get to work," Krupenkin emphasizes. Placing zinc only on the bottom involved "one huge challenge after another," he recalls. To deposit metals in specific places, scientists typically use a process known as electroplating. Electroplating does not work on oxides such as the silicon dioxide in the nanograss device, however. So a way had to be devised to make the silicon floor free of silicon dioxide, allowing the zinc to grow on it, while leaving the silicon pillars covered with the oxide. The solution was to coat both the silicon floor and pillars with the oxide but to leave the layer on the floor the thinnest. The oxide was etched away from the entire device using ionized gas, until the floor had no oxide, although the pillars still did.

SLIM FILMS

Yet electroplating does not work on silicon either. So the researchers used wet-chemistry techniques to deposit nickel or titanium on the floor as a seed layer for zinc to stick to during electroplating. Growing zinc in a uniform manner so that there were not small mountains of zinc in some places and none elsewhere required laborious trial and error by fiddling with temperatures, electric current and concentrations of chemicals. "Looking back, I'm surprised it took only a year," Simon remarks.

After the scientists had a prototype working, they began to talk to potential customers. These discussions triggered a radical revamping of the battery. The initial design was a sandwich, with the cathode on top, the zinc chloride electrolyte solution in the middle, the nanograss under it and the anode on the bottom. Officials at the U.S. Army Research Laboratory in Adelphi, Md., expressed concern about how constant contact between the electrolyte and any electrode could result in unwanted chemical reactions. After the redesign, electrolyte now rests on top, the anode and cathode compounds occupy physically separated patches on the bottom, and a nanosilicon barrier is suspended in between, which, when activated, enables the electrolyte to penetrate and immerse the electrodes.

The team originally used nanopillars to separate the electrolyte from the anode because the pillar took up the least amount of space, allowing more surface area for chemical reactions between those electrodes. But the difficulty of manufacturing the nanopillar battery design prompted researchers instead to develop a nanohoneycomb membrane to isolate the electrolyte from the electrodes. Creation of the electrowetting membrane, with pores 20 microns across and thin, fragile walls 600 nanometers wide, was also a challenge. First the scientists used a plasma to etch the delicate honeycomb structure from wafers of silicon covered in silicon dioxide. Then they grew silicon dioxide on the bare silicon walls of the pores in furnaces heated to 1,000 degrees Celsius and suffused with oxygen. Finally, they coated the entire honeycomb with fluorocarbon.

The researchers developed their first redesigned samples in October 2005. One of the great advantages of the system is that it now helps the team avoid having to laboriously find the exact conditions required to grow a uniform anode layer amid a forest of nanopillars every time it wants to try out a new anode-cathode combination. Instead the scientists can simply lie the electrode patches down on otherwise featureless surfaces. At the same time, the experience they gained in electroplating should make creating the patches far easier, Simon notes. Bell Labs and mPhase are currently collaborating with Rutgers University on incorporating the kind of lithium-based battery chemistries found in digital cameras and cellular phones.

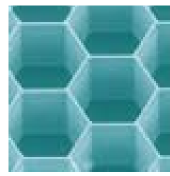
The nanobattery might also allow for a more environmentally friendly power source that includes compounds that can entomb the electrolyte. "That would keep it from leaching into the ground or, if soldiers got shot, would keep the battery from leaking all over them," Krupenkin says. Plastic nanostructures might also be used in place of employing silicon, Simon adds, potentially paving the way for flexible nanobatteries.

The scientists are not seeking to replace disposable batteries, since mass production of those "is in the fractions of cents per AA battery," Krupenkin says. Instead they are targeting more specialized applications, such as sensors dropped from military aircraft that may have to use their radio transmitters just once or twice in their lifetimes, to signal the presence of intruders, for instance, or toxins or radiation. "If the sensor sees nothing interesting, it has nothing to transmit, but if it does, it needs a lot of power," Krupenkin explains. Alternatively, devices monitoring environmental change could use that extra juice to transmit over larger distances, thereby cutting down on the number of sensors needed. Emergency reserve batteries might also be incorporated into medical implants, cell phones or radio-transmitting pet collars.

The team has considered a rechargeable version of their device. A pulse of current could run through a depleted nanobattery, causing the surface on which the electrolyte rests to heat. That could evaporate a tiny layer of the liquid, forcing the droplet to jump up back on top of the nanostructure. "In principle, it's possible. In practice, it's really far out," Krupenkin cautions. For instance, mPhase expects to get product samples to potential first adopters in two to three years. A nanobattery would demonstrate how power sources are finally beginning to keep pace with the revolution in miniaturization that has driven the rest of the electronics industry for decades. SA

Charles Q. Choi is a frequent contributor to Scientific American.

A nanomembrane separated the electrolyte from the electrodes in a later battery design.



BELL LABS, LUCENT TECHNOLOGIES (*nanomembrane*)

MORE TO EXPLORE

From Rolling Ball to Complete Wetting: The Dynamic Tuning of Liquids on Nanostructured Surfaces. T. N. Krupenkin, J. A. Taylor, T. M. Schneider and S. Yang in *Langmuir,* Vol. 20, pages 3824–3827; May 11, 2004.

A film about one phase of development of the nanobattery is available at **www.mphasetech.com/video/mphase.mov**

A Novel Battery Architecture Based on Superhydrophobic Nanostructured Materials. V. A. Lifton and S. Simon. **www.mphasetech.com/nanobattery_architecture.pdf**

Patents on DNA have not caused the severe disruption of biomedical research

OWNING

By Gary Stix

There is a gene in your body's cells that plays a key role in early spinal cord development. It belongs to Harvard University. Another gene makes the protein that the hepatitis A virus uses to attach to cells; the U.S. Department of Health and Human Services holds the patent on that. Incyte Corporation, based in Wilmington, Del., has patented the gene of a receptor for histamine, the compound released by cells during the hay fever season. About half of all the genes known to be involved in cancer are patented.

Human cells carry nearly 24,000 genes that constitute the blueprint for the 100 trillion cells of our body. As of the middle of last year, the U.S. Patent and Trademark Office had issued patents to corporations, universities, government agencies and nonprofit groups for nearly 20 percent of the human genome. To be more precise, 4,382 of the 23,688 genes stored in the National Center for Biotechnology Information's database are tagged with at least one patent, according to a study published in the October 14, 2005, *Science* by Fiona Murray and Kyle L. Jensen of the Massachusetts Institute of Technology. Incyte alone owns nearly 10 percent of all human genes.

The survey of the gene database confirmed that the patenting of life is today well established. Yet it still strikes a lot of people as bizarre, unnatural and worrisome. "How can you patent my genes?" is often the first question that comes up. How can someone own property rights on a type of mouse or fish when nature, not humans, "invented" its genes? What happens to the openness of scientific research if half of all known cancer genes are patented? Does that mean that researchers must spend more time fighting in the courts than looking for a cure?

Ethicists, judges, scientists and patent examiners continue to immerse themselves in these debates, which will only grow more acute in a new era of personalized medicine and of genomics and proteomics research that examines the activities of many different genes or proteins at the same time. Doctors will rely increasingly on patented tests that let clinicians match genetically profiled patients with the best drugs. Investigators are already assessing the functioning of whole genomes. Potentially, many of the biological molecules deployed in these complex studies could come burdened with licensing stipulations that would prevent research leading to new therapies or that would fuel the nation's already robust health care inflation.

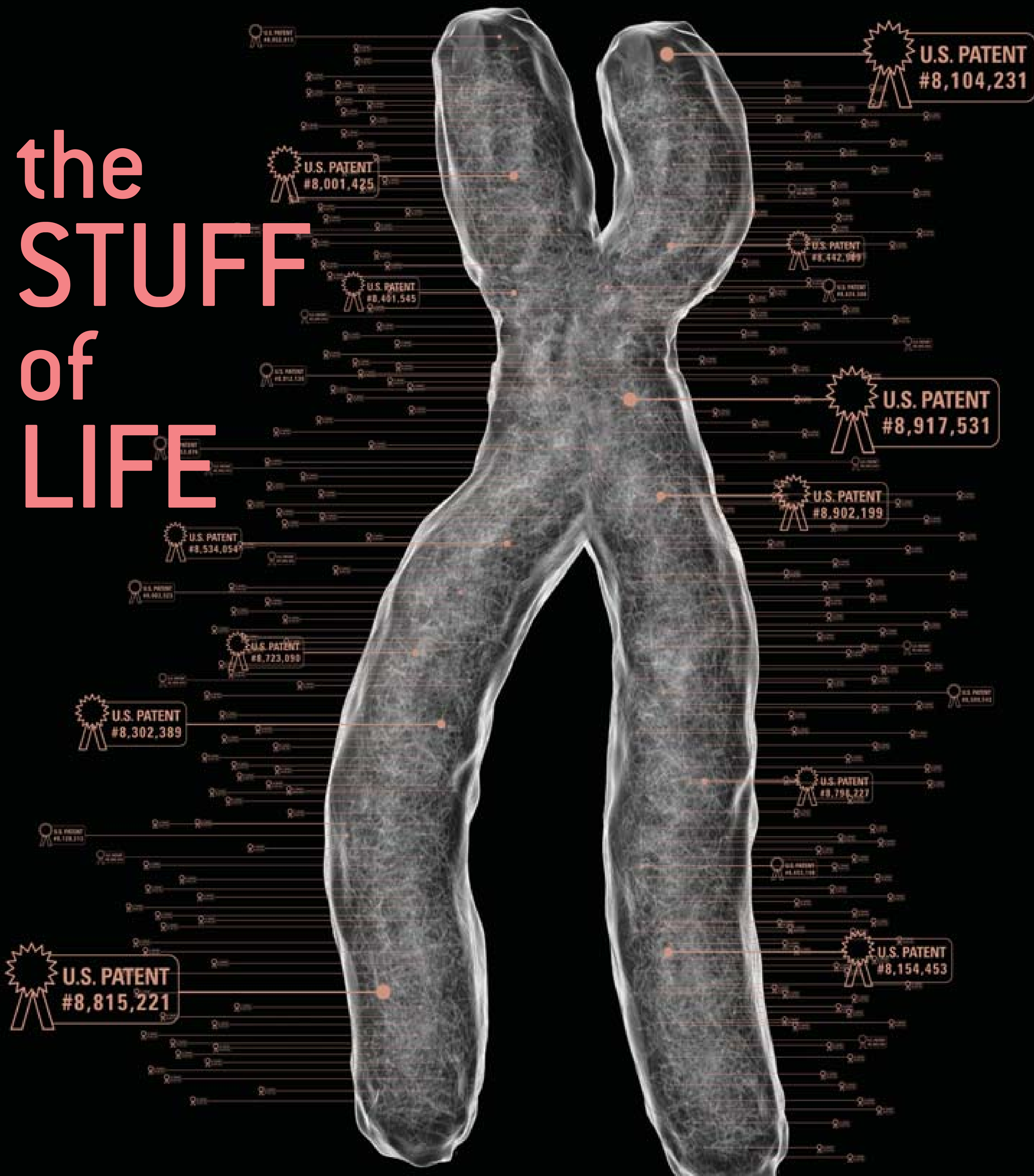
Anything under the Sun

THE QUESTION of "who owns life" has been asked before. But the M.I.T. researchers' taking stock of the intersection of intellectual property and molecular biology came fittingly at the 25th anniversary of a landmark decision by the U.S. Supreme Court that

BRYAN CHRISTIE DESIGN

and societal norms anticipated by critics. But the deluge may be yet to come

the STUFF of LIFE



held that living things are patentable—as long as they incorporate human intervention—in essence, that they are "made" by humans.

Ananda M. Chakrabarty, a General Electric engineer, filed for a patent in 1972 on a single strain of a *Pseudomonas* bacterium that could break down oil slicks more efficiently than if a bioremediation specialist deployed multiple strains for the task. Chakrabarty did not create his strain by what is usually meant by genetic engineering—in fact, recombinant DNA splicing methods were not invented until the year of his filing. Instead he tinkered with the bacterium in a more classical way and coaxed it to accept plasmids (rings of DNA) from other strains with the desired properties. The patent office rejected Chakrabarty's application, saying that "products of nature" that are "live organisms" cannot be patented.

By the time the Supreme Court decided to hear the appeal of the case in 1980, the landscape of molecular biology was changing radically. The splicing of DNA from one organism to another had become commonplace. A new firm called Amgen had formed that year to take advantage of the nascent technology of cutting and pasting DNA. A paper had just appeared detailing how recombinant methods had been used to synthesize interferon. Stanley Cohen and Herbert Boyer received a patent on a key technology for manipulating DNA. Technological boosterism was in the air. Congress passed the Bayh-Dole Act, which allows universities to engage in exclusive licensing agreements for technology they have patented. The Stevenson-Wydler Act let the National Institutes of Health and other federal agencies do the same.

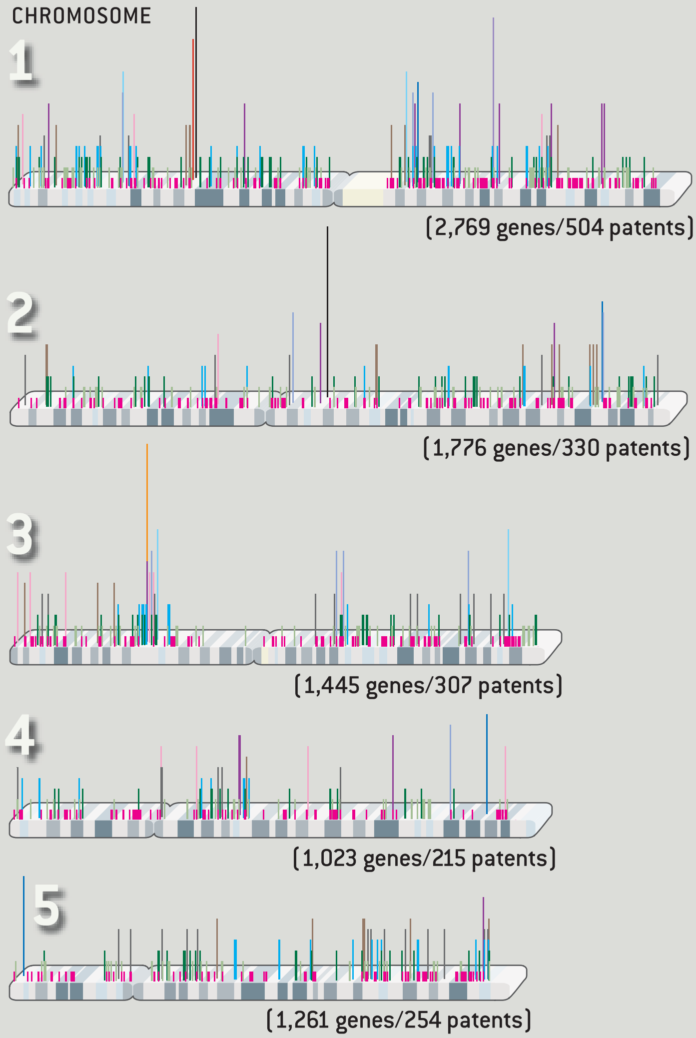
The Supreme Court justices received friend-of-the-court briefs arguing both for and against granting the claims in the Chakrabarty patent. Groups ranging from Genentech to the Regents of the University of California urged that the patent application be granted, citing benefits for pharmaceutical development, environmental remediation and new sources of energy, to name a few. The Peoples Business Commission, co-directed by activist Jeremy Rifkin, decried the commodification of life and described environmental disasters in the offing.

Overview/*Genetic Patenting*

- Last year marked the 25th anniversary of the landmark court decision that opened a floodgate of patenting on both DNA and even whole organisms.
- Nearly one fifth of the nearly 24,000 genes in the human genome have one or more patents on them. Almost 50 percent of known cancer genes have been patented.
- Overall the feared blocking of basic research by ownership of both gene-based tools and critical knowledge has not yet occurred, but it still could materialize as genomic and proteomic discoveries are commercialized.
- In the U.S., ethical issues about patenting life have been largely ignored in enacting legal decisions and policy, but they are still a consideration in Europe and Canada.

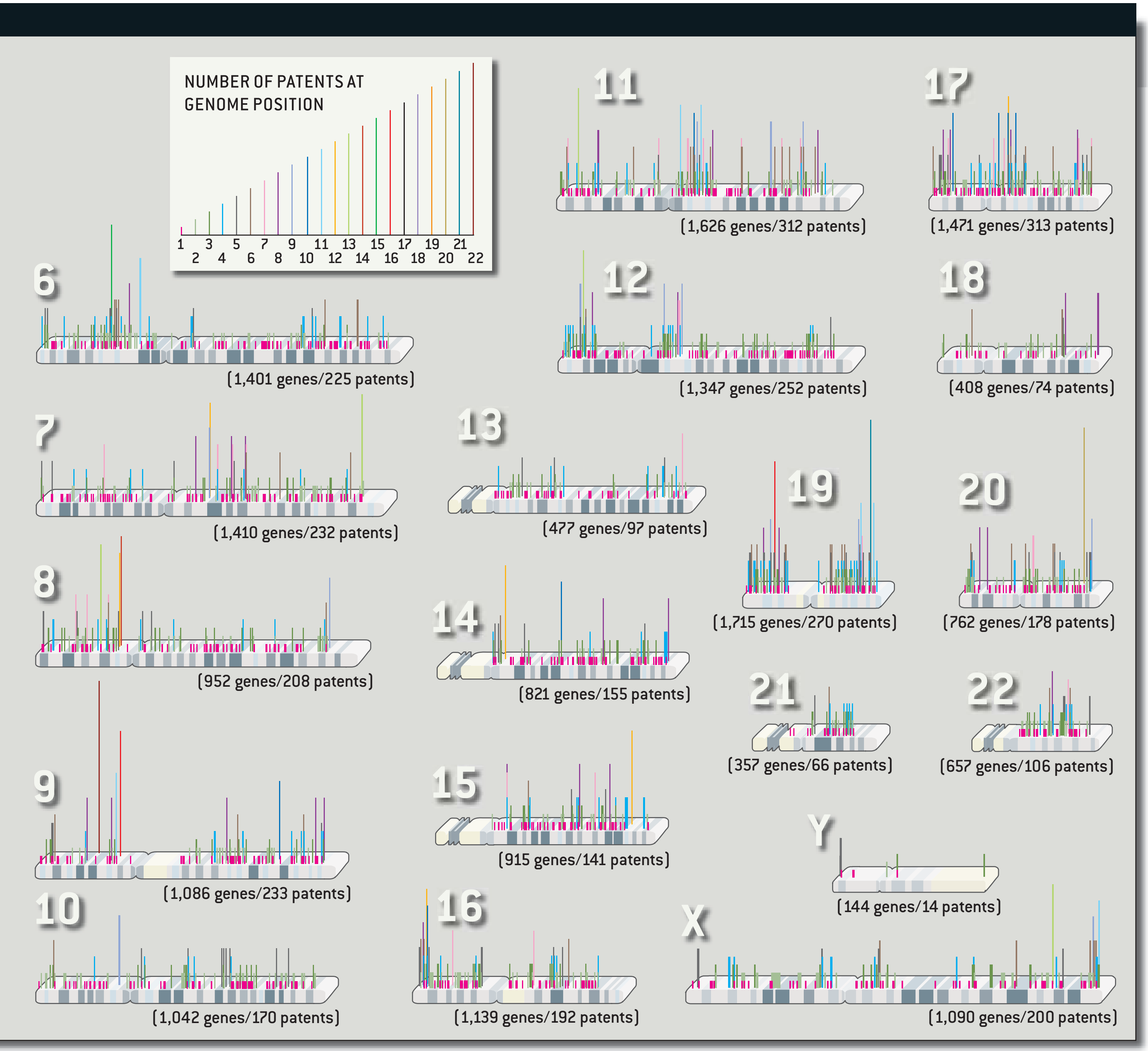
THE HUMAN PATENTOME

This map of the chromosomes offers an indication of how often genes have been patented in the U.S. Each colored bar represents the number of patents in a given segment of a chromosome, which can contain several genes. Patents can claim multiple genes, and one gene may receive multiple patents. As a result, the number of patents indicated for each chromosome does not necessarily match the sum of the values represented by the colored bars.



LAURIE GRACE; SOURCE: KYLE JENSEN AND FIONA MURRAY *Massachusetts Institute of Technology*

In the majority opinion, Chief Justice Warren Burger waved away the objections to patenting life as irrelevant, saying that "anything under the sun that is made by man" could be patented. The only question for the court was whether the bacterium was a "product of nature" or a human invention. "Einstein could not patent his celebrated law that $E = mc^2$; nor could Newton have patented the law of gravity," the opinion acknowledged. But as a "product of human ingenuity," Chakrabarty's engineered bacterium was different. Dismissing Rifkin's "gruesome parade of horribles," the court suggested that it was incapable of standing in the way of progress. "The large amount of research that has already occurred when no researcher had sure knowledge that patent protection would be available sug-



gests that legislative or judicial fiat as to patentability will not deter the scientific mind from probing into the unknown any more than Canute could command the tides," Burger noted.

After the close 5–4 ruling, industry and academia have looked to the broad interpretation of patentability in the Chakrabarty case as justification for patenting not only genes but other stuff of life, whole organisms and cells—including stem cells—to give but an incomplete list. The early patents on genes followed closely in the tradition of patents on chemicals. Incyte does not actually own the rights to the gene for the histamine receptor in your body but only to an "isolated and purified" form of it. (At times, patent examiners or courts have invoked the U.S. Constitution's prohibition of slavery to explain why a patent cannot be issued on an actual human or on his or her body parts.) A patent on an isolated and cloned gene and the protein it produces grants the owner exclusive rights to market the protein—say, insulin or human growth hormone—in the same way that a chemical manufacturer might purify a B vitamin and file for a patent on it.

Little Effort, Less Originality

BY THE 1990S the inexorable pace of technological development had overturned the status quo again. The high-speed sequencing technologies that emerged during that decade—which powered the Human Genome Project—muddied the simple analogy with chemical patenting.

An expressed sequence tag (EST) is a sequenced segment of DNA only a few hundred nucleotides long located at one end of a gene. It can be used as a probe to rapidly fish out the full-length gene from a chromosome. Researchers started filing patents on ESTs—sometimes by the hundreds. They did so without really knowing what the ESTs in question did: the applicants often guessed at the biological function of the gene fragments by poking through protein and DNA databases. "This involves very little effort and almost no originality," once remarked Bruce Alberts, former president of the National Academy of Sciences.

The justification for patenting DNA sequences of unclear function was that these ESTs could serve as research tools. Yet this reason was precisely what concerned much of the scientific community. Owners of patents on EST probes might demand that researchers license these tools, adding expense and red tape to medical research and possibly impeding the development of new diagnostics and therapeutics.

In a 1998 article in *Science*, Rebecca S. Eisenberg of the University of Michigan Law School and Michael A. Heller, now at Columbia Law School, worried about the emergence of an "anticommons," the antithesis of the traditional pool of common knowledge that all scientists share freely. Those concerns were heightened by the audacious scope of some of these applications, which staked out not only the ESTs but any DNA that resides adjacent to them. Such a claim could translate, in theory, into granting property rights for an entire chromosome.

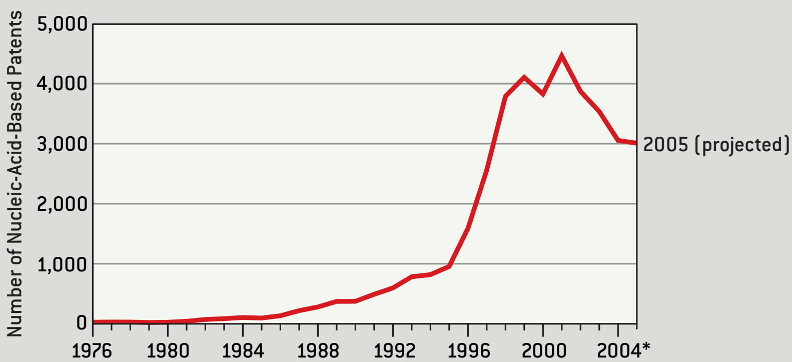
But a further, more intellectual objection to the concept of these patents was that the use of ESTs to pin down the location of genes actually occurs in a database, not in a laboratory. The value of ESTs exists more as information than as one of the tangible "processes, machines, manufactures and compositions of matter" that are eligible for patenting. Abstract ideas have traditionally been considered outside the realm of patentable subject matter, although a number of federal court cases have blurred this distinction during the past 10 years.

Allowing information to be patented would tend to undermine the balancing act that is a cornerstone of the whole system. In exchange for a 20-year monopoly, the patent applicant must disclose how to make an invention so that others can use that knowledge to improve on existing technology. But how does the traditional quid pro quo work if the information disclosed to others is the patented information itself? Does the

WHO OWNS THE PATENTS?

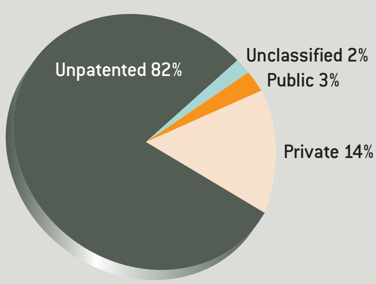
YEARLY U.S. PATENTS RELATED TO DNA OR RNA

The granting of patents involving nucleic acids, including from nonhumans, peaked in 2001 and then declined (*graph*), probably because of tightening requirements. The holders of many of the patents are listed in the table (*right*).



PATENTS ON HUMAN GENES

As the pie chart shows, private interests in the U.S. were the largest holders of patents on the 23,688 human genes in the National Center for Biotechnology Information database in April 2005.



LARGEST PATENT HOLDERS	NUMBER OF PATENTS†
University of California	1,018
U.S. government	926
Sanofi Aventis	587
GlaxoSmithKline	580
Incyte	517
Bayer	426
Chiron	420
Genentech	401
Amgen	396
Human Genome Sciences	388
Wyeth	371
Merck	365
Applera	360
University of Texas	358
Novartis	347
Johns Hopkins University	331
Pfizer	289
Massachusetts General Hospital	287
Novo Nordisk	257
Harvard University	255
Stanford University	231
Lilly	217
Affymetrix	207
Cornell University	202
Salk Institute	192
Columbia University	186
University of Wisconsin	185
Massachusetts Institute of Technology	184

† as of 9-14-05

LAURIE GRACE; SOURCES: KYLE JENSEN AND FIONA MURRAY *Massachusetts Institute of Technology* (*pie chart and graph*); LORI PRESSMAN, ROBERT M. COOK-DEEGAN AND LEROY WALTERS ET AL. IN *NATURE BIOTECHNOLOGY* (IN PRESS) AND MELISSA SOUCY *Kennedy Institute of Ethics, Georgetown University* (*table*)

PATENTING LIFE: A CHRONOLOGY

The patent system—both courts and patent examiners—has always wrestled with the question of what is truly an invention (and therefore deserving of a patent) and what constitutes a mere attempt to expropriate in unaltered form a physical law or material from the natural world, a reason for rejecting an application.

1889
The commissioner of patents determines that plants, even artificially bred ones, are "products of nature," and therefore ineligible for patenting. The applicant in this case—*Ex parte Latimer*—had tried to patent fibers separated from the plant and was turned down


Iris

1930
The U.S. Congress passes the Plant Patent Act, which allows the patenting of new plant varieties that reproduce asexually

1948
A Supreme Court ruling held that simply combining bacteria does not count as an invention (*Funk Brothers Seed Company v. Kalo Inoculant Company*)

1971
Cetus, the first biotechnology company, opens its doors

Continued on next page

mere act of using that information in the course of conducting scientific research run the risk of infringement?

In response to some of these pressures, in 2001 the U.S. patent office made final new guidelines that directed examiners to look for "a specific and substantial utility" in granting biotechnology patents. In most other technological pursuits, the requirement that a patent be useful is secondary to criteria such as whether an invention is truly new, because most inventors do not seek protection for worthless inventions. In the arena of life patents, the assessment of an invention's usefulness has become a crucial filter to maintain a check on patent quality. Designating a sequence of DNA simply as a gene probe or chromosome marker is not enough to meet the new rules.

These changes have had an effect. So far only a small number of EST patents have been issued, according to the NAS. An important affirmation of the patent office's approach to weeding out useless and overly broad patents came in a decision on September 7, 2005, by the U.S. Court of Appeals for the Federal Circuit (CAFC), which hears appeals of patent cases. The court upheld the patent office's denial of Monsanto's application for a patent for five plant ESTs that were not tied to a given disease. The patents would have amounted to "a hunting license because the claimed ESTs can be used only to gain further information about the underlying genes," wrote federal circuit chief judge Paul Michel.

Data on the extent of a feared anticommons have just begun to emerge in recent months. A survey performed as part of an NAS report—"Reaping the Benefits of Genomic and Proteomic Research," released in mid-November 2005—received responses from 655 randomly selected investigators from universities, government laboratories and industry about the effect of life patents on genomics, proteomics and drug development research. The study found that only 8 percent of academics indicated that their research in the two years prior had anything to do with patents held by others; 19 percent did not know if their research overlapped; and 73 percent said that they did not need to use others' patents. "Thus, for the time being, it appears that access to patents or information inputs into biomedical research rarely imposes a significant burden for academic biomedical researchers," the report concluded.

The number of patents actively being sought has also declined substantially. Patents referring to nucleic acids or closely related terms peaked at about 4,500 in 2001, according to a recent report in *Nature Biotechnology,* and declined in four subsequent years—a trend that may result, in part, from the patent office's tightening of its utility requirement [*see box on opposite page*].

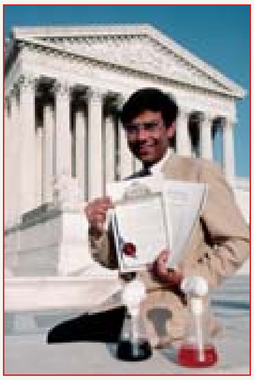
Some of the downturn may relate to the success of a de facto open-source movement in the biomedical sciences, akin to the one for information technologies. In 1996 scientists from around the world in both the public and private sectors devised what are referred to as the Bermuda Rules, which specify that all DNA sequence information involved in the Human Genome Project should be placed immediately into the public domain. Data sharing was later encouraged in other large-scale projects, such as the Single Nucleotide Polymorphism Consortium, which mapped genetic variation in the human genome. In some cases, researchers have taken out patents defensively to ensure that no one else hoards the knowledge. Both companies and public health groups involved with discovering and sequencing the SARS virus are trying to form a "patent pool" to allow nonexclusive licensing of the SARS genome.

This embrace of the public domain torpedoed the idea of building a business on public information. Both Celera Genomics and Incyte—two leaders in the genomics field—restructured in the early years of the new century to become drug discovery companies. J. Craig Venter, who spearheaded the private effort to sequence the human genome, left Celera and turned into an open critic. "History has proven those gene patents aren't worth the paper they were written on, and the only ones who made money off them were the patent attorneys," Venter commented at a 2003 conference.

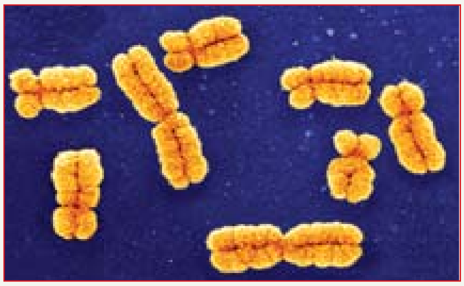
A patent thicket that blocks basic research has also failed to materialize because academics tend not to respect intellec-

ANONYMOUS/PRIVATE COLLECTION/BRIDGEMAN ART LIBRARY (*iris*)

1980
The Supreme Court rules that Ananda Chakrabarty's bacterium is not a "product of nature" and so can be patented; other living things "made by man" are declared patentable as well

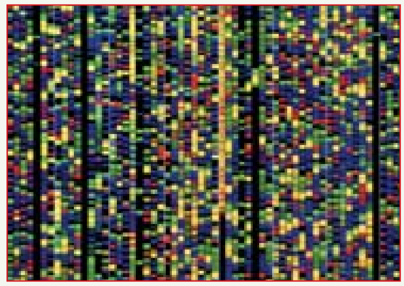

Ananda Chakrabarty

Congress passes the Bayh-Dole Act (the Patent and Trademark Laws Amendment), which allows universities to enter into exclusive licensing for their intellectual property


Human chromosomes

1988
Harvard University gets a patent for the OncoMouse, a rodent with a gene inserted that predisposes it to cancer

1990
The Human Genome Project is launched


DNA sequencing

1996
Both public- and private-sector scientists from all over the world involved in DNA sequencing pass a resolution—the Bermuda Rules—that states that "all human genomic sequence information, generated by centers funded for large-scale human sequencing, should be freely available and in the public domain"

tual property. Noncommercial research, in their view, receives an exemption. Yet a 2002 case decided by the CAFC—*Madey v. Duke*—disabused universities and other nonprofit institutions of any notion of special status. The court decided that noncommercial research furthers the "legitimate business objectives" of a university, and so both research tools and materials, which would include DNA, do not merit an exemption. (An exemption does exist for research that is specific to preparing an application to file for a new drug.)

Patent holders generally have little interest in beating down lab doors to track down infringers. In the wake of the *Madey* decision, the level of notification from patent owners has picked up a bit, according to the NAS survey, but this increase has not caused major disruption. A growing awareness of the absence of an exemption, however, could lead to a more restrictive research environment, which is why the NAS panel recommended that Congress put in place a statutory research exemption.

Major intellectual-property hurdles may begin to appear as genomics and proteomics—fields in which many genes or proteins are studied together—reach maturation. "The burden on the investigator to obtain rights to the intellectual property covering these genes or proteins could become insupportable, depending on how broad the scope of claims is and how patent holders respond to potential infringers," the NAS panel remarked.

Genomics and proteomics are only starting to bear fruit in the form of medical diagnostics and drugs. "You really get ownership issues coming up when things get closer to market," says Barbara A. Caulfield, general counsel for Affymetrix, the gene-chip company that has opposed DNA patenting because it could impede research with its products.

Already, Caulfield says, examples of patents with a very broad scope burden both industry and academia. Genetic Technologies Ltd., an Australian company, holds patents that it is using to seek licensing arrangements from both companies and universities that conduct research on the noncoding portion of the genome. The breadth of its patents—covering methods of obtaining information from the approximately 95 percent of the genome that is sometimes erroneously called junk DNA—would make most scientists rub their eyes. Genetic Technologies, however, has already entered into licensing arrangements with the likes of U.S. biotechnology giant Genzyme and Applera, the parent of Celera and Applied Biosystems.

Keeping the *Ordre Public*

U.S. POLICYMAKERS and courts have, in general, taken a no-holds-barred approach to the commercialization of new biotechnologies. Though often debated by government advisory panels, ethical, philosophical and social questions have seldom entered into actual decision making about whether to extend patent protection to living things. In *Chakrabarty*, the Supreme Court justified its decision, in part, by quoting the statement of the first patent commissioner, Thomas Jefferson, that "ingenuity should receive a liberal encouragement."

One of the obvious questions raised by the *Chakrabarty* decision was, Where does patenting life stop? Does it extend to creatures above the lowly *Pseudomonas* on the phylogenetic tree? In 1988, eight years after *Chakrabarty*, the patent office issued No. 4,736,866, the patent for the Harvard OncoMouse, which contained a gene that predisposed the animal to contract cancer, a valuable aid in researching the disease. The justification for granting the patent could be traced directly to the reasoning of the justices in *Chakrabarty:* the addition of the oncogene meant that this was a mouse "invented" by a human.

Not every country has handled the issue of patenting higher organisms with the same utilitarian bent demonstrated by U.S. courts and bureaucrats. Much more recently, Canada reached an entirely different decision about the small mammal with the extra gene. On appeal, the Supreme Court of Canada rejected the Harvard OncoMouse patent. In 2002 it decided that the designation "composition of matter"—in essence, an invented product that is eligible for patenting—should not apply to the mouse. "The fact that animal life forms have numer-

TED SPIEGEL *Corbis* (*Chakrabarty*); BIOPHOTO ASSOCIATES/PHOTO RESEARCHERS, INC. (*chromosomes*); DAVID PARKER *Photo Researchers, Inc.* (*DNA sequencing*)

Cancer mice

2000
A working draft of the human genome is announced

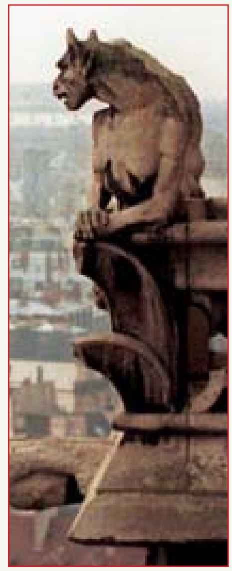
Heads of state Bill Clinton and Tony Blair issue a statement that "raw fundamental data on the human genome, including the human DNA sequence and its variations, should be made freely available to scientists everywhere." Biotechnology stocks drop sharply

2001
The U.S. patent office issues final guidelines that raise the standard for usefulness and the amount of disclosure of details of an invention needed for granting, in part, patents—an action prompted by the many patent applications on gene fragments

2002
The Supreme Court of Canada hears an appeal that results in the refusal of a patent for the Harvard OncoMouse

2003
Congress puts a provision in the patent office budget prohibiting patents on a "human organism," a codification of the office's existing policy

2005
The patent office issues a final rejection of a patent application filed by Stuart Newman and Jeremy Rifkin for a hypothetical chimera: a part-human, part-animal hybrid. The two opponents of patents on living things want to obtain a patent to block anyone from ever creating such an animal



Chimera

ous unique qualities that transcend the particular matter of which they are composed makes it difficult to conceptualize higher life forms as mere 'compositions of matter,' " Justice Michel Bastarache asserted. "It is a phrase that seems inadequate as a description of a higher life form."

Europe, too, was more circumspect than the U.S. about embracing the cancer mouse. The European Patent Office narrowed the scope of the OncoMouse patent to cover only mice instead of all rodents. It did so by invoking a provision of its patent law that has no comparable clause in U.S. statutes. It brought to bear Article 53 of the European Patent Convention, which bars patents that threaten " '*ordre public*' or morality."

European regulators have also eviscerated the patent portfolio on breast cancer genes held by the Utah-based Myriad Genetics. In the U.S., patents on diagnostic genes, more than other DNA patents, have inhibited both research and clinical medicine. Myriad has used its patents to stop major cancer centers from devising inexpensive "home-brew" tests for the breast cancer genes *BRCA1* and *BRCA2*. In Europe, a coalition of research institutes challenged Myriad's patents, invalidating some and limiting others. Because of the paring back of Myriad's rights, the tests are now free for everyone except Ashkenazi Jewish women, who must pay Myriad's licensing fees. The mutations that are still covered by Myriad's remaining patents are most commonly found in Ashkenazi women. By law, a doctor must ask a woman if she is an Ashkenazi Jew, which has provoked howls from geneticists.

A replay of these scenes is unlikely in the U.S. In *Chakrabarty,* the Supreme Court remarked that the type of ethical questions raised by Rifkin's group should be addressed by Congress, but most legislative attempts have foundered so far. If any fundamental change does come, it will most likely happen through the Supreme Court's examination again of one of the key decision points in *Chakrabarty:* the definition of the ever shifting line between laws of nature and invention.

Legal analysts are eagerly awaiting a Supreme Court decision expected this year that may help clarify how far to push back the borders of what was once considered unpatentable. The high court has agreed to hear a case—*Laboratory Corp. of America Holdings v. Metabolite Laboratories, Inc.*—that will determine whether the simple correlation of an elevated level of the amino acid homocysteine with a deficiency of two B vitamins "can validly claim a monopoly over a basic scientific relationship used in medical treatment such that any doctor necessarily infringes the patent merely by thinking about the relationship after looking at a test result," in the language of Laboratory Corp., the plaintiff. The patent claim covers only the correlation itself, not the electrical and mechanical equipment that is used to carry out the test. The case is of intense interest not only to a biotechnology industry in which raw information has become increasingly valuable but also to the information technology industry, where the patentability of software and business methods has also been a matter of dispute. "This could have an impact not just on DNA patenting but on emerging areas such as nanotechnology and synthetic biology," says Arti K. Rai, a law professor at Duke University.

Friend-of-the-court briefs will argue that the Jeffersonian doctrine of promoting invention should prevail. But the case also resonates with *Chakrabarty* and case law that preceded it. As technology advances, courts will have to come to grips again and again with defining the meaning of the phrase "anything under the sun that is made by man." Should tinkering with a single gene in a mouse—or the mere act of detecting an inverse relation between two molecules—suffice always to confer on an "inventor" a limited monopoly for two decades? SA

MORE TO EXPLORE

Who Owns Life? Edited by David Magnus, Arthur Caplan and Glenn McGee. Prometheus Books, 2002.

Intellectual Property Landscape of the Human Genome. Kyle Jensen and Fiona Murray in *Science,* Vol. 310, pages 239–240; October 14, 2005.

Reaping the Benefits of Genomic and Proteomic Research: Intellectual Property Rights, Innovation, and Public Health. Committee on Intellectual Property Rights in Genomic and Protein Research and Innovation. National Research Council, National Academies Press, 2005.

SCIENCE MUSEUM/SCIENCE AND SOCIETY PICTURE LIBRARY (*mice*); REMY DE LA MAUVINIERE *AP Photo* (*chimera*)

DIGITAL RECONSTRUCTION reveals how Washington probably looked at 19 years of age.

By Jeffrey H. Schwartz

Putting a face on the first President

Solving a surprisingly long-standing mystery, a forensic anthropologist reconstructs what George Washington looked like as a young man

Among the few things I remember from grade school about George Washington is that as a youth he chopped down a cherry tree and then confessed the deed to his father, and as an adult, he wore wooden dentures. Recently I learned quite a bit more about Washington. It turns out he never chopped down a cherry tree. He didn't wear wooden dentures either. But those were the least of the surprises.

An unexpected invitation to reconstruct the first president as he looked in his younger years—before the famous portraits and statue—sent me on a hunt that revealed a very different Washington from the unapproachable, thin-lipped elder statesman on the dollar bill. My foray into American history started when James C. Rees, executive director of Mount Vernon, Washington's estate, asked me whether I could re-create the way Washington, who was born in 1732 and died in 1799, had looked at three important points in his life. Rees wanted these life-size figures for Mount Vernon's new education center, which will open in the fall of 2006.

The 19-year-old Washington would be depicted in 1751, during his early career as an adventurer and surveyor. The 45-year-old would be shown in 1777, when he and his troops were bivouacked during the dreadful winter at Valley Forge, waiting for a chance to attack the British, who had occupied the city of Philadelphia. These two figures would complement a third portrayal, the 57-year-old Washington being sworn in on April 30, 1789, as the first president, a role he chose instead of the alternative he had been offered: becoming king.

As a physical anthropologist, I have studied early hominid bones and reconstructed specimens of our predecessors. My work as a forensic anthropologist for the Allegheny County, Pennsylvania, coroner's office has augmented this experience. But nothing prepared me for the curious challenges involved in figuring out what Washington actually looked like. One of the first things I learned was that I would not be allowed to study his skeleton, which would remain buried. No bones? How could I begin to imagine doing a forensic reconstruction without bones? But the challenge was too intriguing to decline.

TOM DRAPER DESIGN

The Clues

AMONG THE MATERIALS I did have to work with were a full-length white marble statue, a bust and a life mask, all by French court sculptor Jean-Antoine Houdon, who had begun his depictions during a visit to Mount Vernon in 1785, when Washington was 53 years old. A handful of portraits from his middle and later years added to the available clues—mainly those by Gilbert Stuart, Charles Wilson Peale and his son Rembrandt Peale, and John Trumbull. Several sets of dentures and a scattering of clothing, also from the later part of his life, could furnish other valuable evidence.

What I needed was some way to combine and manipulate these clues. If I could three-dimensionally scan Houdon's life mask, bust and statue, for example, I could compare them for accuracy of detail. If I could three-dimensionally scan surviving dentures, I could insert them into the digital head to determine the curvature of the jaws. Then I could try to estimate how much bone Washington had lost from his jaws by the time he was 53 (probably a close approximation to his jaws at age 57) and replace it as I worked my way through making him progressively younger.

As soon as I realized I would need to operate in the three-dimensional digital realm, I thought of PRISM, the Partnership for Research in Spatial Modeling, at Arizona State University. I had visited its laboratory when I gave a talk at the university, and I remembered seeing the results of collaborations involving sculptors, physical anthropologists, engineers and computer scientists. Although other labs were also expert in 3-D digital imaging, PRISM already had a track record of working with physical anthropologists, which meant that we shared a common scientific language. I presented the project to Anshuman Razdan, then PRISM's director, who to my delight agreed to help with the imaging.

I decided to start with Houdon's depictions of the 53-year-old Washington. I began with Houdon in part because the sculptor is legendary for his meticulous technique. According to contemporary accounts, he had used calipers to measure the president from head to toe. Unfortunately, Houdon's studio and all his notes were destroyed during the French Revolution,

Overview/*Reconstructing GW*

- The author, a physical anthropologist, was asked to make the first forensic reconstruction of George Washington. Part of a new education center at Mount Vernon, the project calls for full-length figures of the first president at the ages of 19, 45 and 57.
- The skeletal remains could not be used to furnish clues. A statue, portraits, a life mask, dentures and clothing—all from the later years of Washington's life—constituted the available evidence.
- A special three-dimensional computer program allowed the author and his colleagues to combine and manipulate these clues to arrive at the three lifelike reproductions.

No bones? How could I begin to imagine doing a forensic reconstruction without bones?

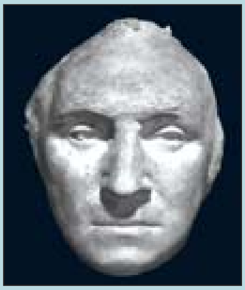
but many experts are nonetheless convinced of the physical accuracy of the bust and statue, which Washington had specifically asked the sculptor not to make larger than life, as was the custom for representing people of importance.

To determine the degree of accuracy, Razdan and his colleagues scanned the bust and the life mask and compared them digitally, finding them to be almost identical. The two differ at most by a statistically insignificant 0.3 millimeter. Surely this proved that the statue and the bust were accurate representations of Washington's face. But something bothered me about the astonishing congruence between the life mask and the bust's face. Documents at Mount Vernon indicate that Houdon had made the bust days before the life mask, which suggests the two would have differed more, because the bust would have been done freehand. Yet the eyes, nose, asymmetrical skewed chin, positions of the exposed earlobes, and creases in the forehead were identical in the life mask and bust. Finally, after months of puzzling, I concluded that Houdon had not created the face in the bust freehand. After he added the eyes to the life mask (they had to be covered when the mold of the face was taken), he then made a mold of the mask and pressed terra cotta into it to achieve the bust's face. I had to take it on faith that the rest of the head was based on Houdon's caliper measurements.

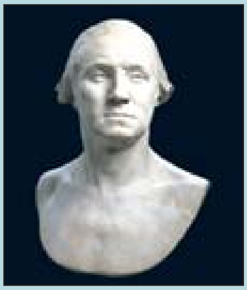
While we were sorting out the information gleaned from the digital scans, I met with Ellen G. Miles, curator of painting and sculpture at the Smithsonian National Portrait Gallery, to begin my education in the accuracy, and thus usefulness, of Washington portraits. From the beginning, she warned that one must be skeptical not only of portraits copied from originals painted by artists for whom Washington posed but of the originals themselves. Take, for instance, Stuart's portrait from the late 1790s, which is one of the few full-length 18th-century paintings of Washington. The face is recognizably Washington's—Stuart probably copied it from his portrait that now hangs in the Boston Athenaeum, the mirror image of which is on the dollar bill—but the hands at least are most likely Stuart's, and the body was fashioned after as many as three models who stood in for Washington.

Trumbull's 1792 portrait, in contrast, may more accurately portray Washington's body from the neck down than from the neck up. An even more impressive example of artistic interpretation turned up when Miles compared portraits that Peale and his 17-year-old son Rembrandt painted simultaneously in 1795, when Washington, then in his 60s, sat for the two of them together. The elder Peale painted a slightly pudgy, compassionate-looking, even rosy-cheeked person: his longtime friend and comrade. The son portrayed a deeply wrinkled, very old, haggard-looking man. Thus, we have at least

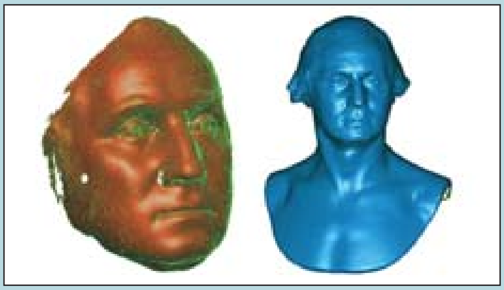
FIRST STEPS IN THE RECONSTRUCTION



Life mask at age 53, by Houdon



Bust at age 53, by Houdon

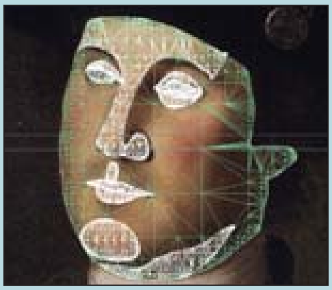


Scan of life mask *Scan of bust*

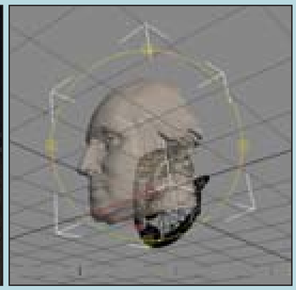
Comparison

The starting point for the reconstruction was sculptor Jean-Antoine Houdon's life mask and bust, made in 1785, when Washington was 53. To determine whether the bust could be used with confidence as a representation of what Washington looked like, the author and his colleagues made three-dimensional computer scans of the mask and the bust and compared them digitally. The result: an insignificant difference of 0.3 millimeter. Yellow denotes areas of contrast: the crucial eye, nose and mouth regions are virtually identical.

Portrait at age 40, by C. W. Peale



Scan of portrait



Importing scan of portrait over bust

Comparison of portrait and bust

For help in working back to the younger Washington, they scanned the earliest existing representation, Charles Wilson Peale's 1772 portrait, painted when the leader was 40. Comparison of this scan and that of the bust revealed that the distance from nose to chin was longer in the painting. The author reasoned that although by the time Washington was 53 he had lost most of his teeth, in his early 40s he probably still had some front teeth, which would have made a difference to the shape of his face. The observed difference gave the author some guidance for how to work backward from the bust and mask to the earlier years.

PIERPONT MORGAN LIBRARY/ART RESOURCE, NY (*life mask*); MOUNT VERNON LADIES' ASSOCIATION (*bust*); WASHINGTON-CUSTIS-LEE COLLECTION, WASHINGTON AND LEE UNIVERSITY (*Peale portrait*)

four "likenesses" of Washington in his 60s, each differing distinctly from the others.

If the portraits were confusing, the dentures were even more so. I quickly learned, of course, that contrary to myth Washington did not wear wooden dentures. In the 1700s the most common material used to form the plates in which teeth (human or animal) were anchored was ivory, often from hippopotamus tusks. Over time, ivory develops hairline cracks along its surface, between the mineralized prisms it is made of. Years of eating, drinking and smoking stain these cracks darker than the enamel prisms. Apparently someone mistook the pattern of staining for the grain of wood, and a legend was born.

What is true is that Washington had lost most of his teeth by the time Houdon visited Mount Vernon. In fact, his first tooth was extracted when he was in his early 20s; by the time he was 53, he may have had only two lower teeth remaining. We do not know the cause of his dental distress, but he may have had progressive periodontal disease, exacerbated by his self-proclaimed addiction to eating walnuts, which he cracked with his teeth. When one loses a tooth, the bone in which the roots were anchored is resorbed, diminishing the height of the jaw in that region. If one loses enough teeth, the jaws—especially the lower—become severely altered in size and shape. This process meant that I had to try to determine the state of Washington's jaws and oral cavity as a 53-year-old before I could think about adding tooth and bone and reshaping the jaws to re-create the 19- and 45-year-olds.

First, I had to track down any surviving dentures that Washington might have worn around this time in his life. It turned out that he had been buried with his last set of dentures. I was able to examine a lower plate made by dentist Joseph Greenwood in 1789, which is at the New York Academy of Medicine, as well as a lower of what had once been a complete set that Greenwood made in 1795, after Washington had lost his last tooth, and that had been in the Smithsonian but is now in the National Museum of Dentistry. The upper had disappeared during a theft from a Smithsonian storeroom. The only complete set I could locate was an initially mysterious pair in the collection at Mount Vernon.

These were found in one of Martha Washington's footlockers many decades after her death. She did not have false teeth, so they presumably belonged to her husband. Nobody knew who had made them or when, although I was able to figure out that they must have been fabricated between 1789 and 1795.

Scholars had determined that the plates were constructed of lead and that the teeth in the upper plate included horse or donkey upper incisors and cow lower incisors and that those in the lower jaw were human teeth, plus one artificial structure supposedly carved from a nut. To my surprise, I saw that some of the teeth in the lower plate were human upper teeth. Even more astonishing was my discovery that the dentures had been essentially unusable. The surfaces of the lead plates were not hollowed out to cup toothless gums; they were flat. Moreover, the springs that held the plates together and pressed them against the gums arced to the rear, not to the sides—their tension would thus have acted to push the dentures out when Washington opened his mouth. The only purpose these dentures could have served was filling space in Washington's oral cavity, perhaps when he was sitting for a portrait. They did, however, tell me something about the size and shape of the president's jaw.

Guided by the dimensions of the false teeth, I began to piece together a model of the inside of Washington's mouth. Later I would worry about melding this information with Houdon's life mask and bust.

Putting the Head Together

WITH MATTHEW TOCHERI, then working at PRISM, I took measurements from the bust that reflected the width of the lower jaw (mandible) where it connects with the base of the skull. Coincidentally, Brenda Baker, an anthropologist at Arizona State, had a small skeletal collection of British soldiers from the French and Indian War. One had a mandible almost as large as Washington's, which we scanned, inserted digitally into the bust's face and scaled up slightly to the correct size. We then aged the mandible by digitally whittling away bone and all the teeth except for the left lower second premolar. We inserted the Mount Vernon dentures digitally on top of the mandible, as they would have sat in Washington's mouth, and adjusted the bone's curve and the location and height of the premolar to fit. We fine-tuned these aspects by scanning a perfect replica of the 1789 Greenwood lower denture into the computer and superimposing it on what we already had. Because the chin of the soldier's mandible and Washington's were not a perfect match, we digitally reshaped the former to produce Washington's broad, obliquely slanted chin line. Using a program that PRISM's Jeremy Hansen wrote for this project, we changed the angle at the back of the mandible to reflect both what I could identify on the life mask as the jawline and the remodeling of bone that would have occurred during almost three decades of tooth loss.

THE AUTHOR

JEFFREY H. SCHWARTZ is a professor in the departments of anthropology and history and philosophy of science at the University of Pittsburgh, a research associate at both the American and Carnegie museums of natural history, and the forensic anthropologist for the Allegheny County, Pennsylvania, coroner's office. His research spans human and nonhuman primate evolution, evolutionary theory, developmental biology, and comparative skeletal morphology. A member of the World Academy of Art and Science, Schwartz is the author of 10 books and more than 150 articles. Among his recent publications are *The Human Fossil Record,* with Ian Tattersall (Wiley-Liss, 2002, 2003, 2005), and *The Red Ape: Orangutans and Human Origins* (Westview, 2005).

The only complete set of dentures I could locate was an initially mysterious pair at Mount Vernon.

Reconstructing the shape of Washington's upper jaw was not as straightforward, because we lacked the stolen upper half of the 1795 Greenwood dentures. The National Museum of Dentistry, however, had a replica of the once-complete original, and I figured that we could scan it as well as the original lower. But when I compared the replica visually with the original lower, I could see noticeable differences: the replica had been cleaned up to look prettier than the fairly gruesome original. Fortunately, the replica and original had been photographed together, so we could scan the replica, and because we knew its size, we could calculate the size of the original. Thus, we were able to produce a three-dimensional upper denture; we modified the soldier's upper jaw to fit into it and adjusted this bony structure to fit, in turn, in the bust's face.

To incorporate this information into the face of a 45-year-old, and ultimately a 19-year-old, I turned to Charles Wilson Peale's portraits of Washington at 40 and 47. After I spent hours staring at them, it struck me that the distance from the nose to chin was longer than that in either the bust or the portraits of Washington at older ages. To confirm this, we compared digitized two-dimensional scans of faces in these paintings with the three-dimensional digital face of the bust. The scans revealed a real difference, and it made sense. Teeth in the back of the mouth are often lost first—the somewhat longer lower facial height of the 40- and 47-year-old Washingtons was quite likely the result of the presence of front teeth and associated bone.

With the portraits as a guide, Hansen used his program to transform the digital face of the 53-year-old to the length of the younger face. Because I also noticed that the chins of the 40- and 47-year-old Washingtons were more symmetrical than in either the life mask or portraits at older ages, we adjusted the chin accordingly. We then imported the soldier's modified jaws into what was now a 40-ish face, adjusted them to fit and checked the image against established data on the thickness of skin. Because the 45-year-old would have had more bone along his mandible than the 53-year-old, the angle at the back had to be better delineated. We finally had the lower face of the 45-year-old. I then used it as the model for the 19-year-old, defining the jaw angle even more in the younger version. For the rest of the face, I softened or removed wrinkles and creases, added some fat to the cheeks (which is lost with age), and shortened the nose and earlobes (because the cartilage in them grows throughout life).

FINISHING THE FACE

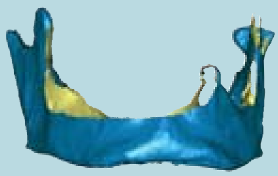
Washington's dental history provided important clues to completing the reconstructions of his head at ages 45 and 19. Tooth loss leads to bone loss, diminishing the height of the jaw and severely altering its size and shape. Once the reconstruction team established the shape of the jaw at 53, they could then add tooth and bone to reshape the jaws so that they took on the structure they had in Washington's younger days.

They began by scanning an actual healthy jaw (*a*) approximately the size of Washington's and inserting it digitally in the 3-D scan of the bust. They then revised the jaw (*b*) by digitally whittling away bone and all teeth except for the lower left second premolar, the one tooth that remained in Washington's head at 57. Finally, they inserted the president's own dentures digitally on top of the jaw (*c*) and adjusted bone and the premolar to fit. Then they could add bone to the jaw (*d*) to re-create the lower facial structure of the 45- and 19-year-olds.

a

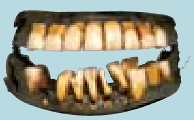
Scan of actual jaw similar in size to Washington's

b

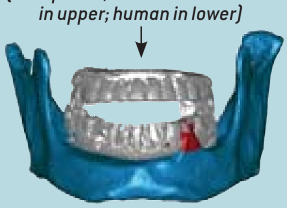


Digitally aged jaw

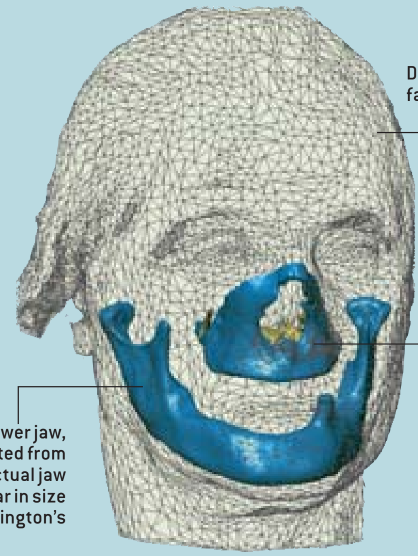
c



Mount Vernon dentures (lead plates, horse and cow teeth in upper; human in lower)



Digitally modeled Mount Vernon dentures inserted into aged jaw

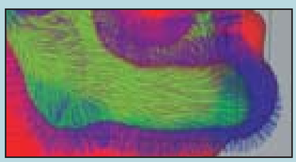


Digital model of face from bust

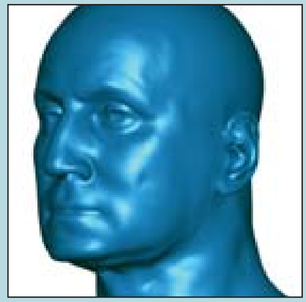
Upper jaw, based on a replica of one of Washington's dentures

Lower jaw, adjusted from actual jaw similar in size to Washington's

d

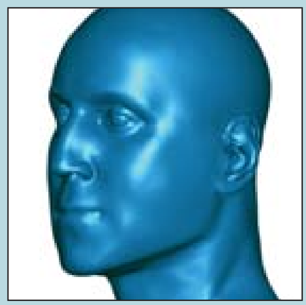


Adjusting the bone on the digitally aged jaw (green) to fit the depth of soft tissue that would have been between it and the skin; purple lines indicate skin depth



57 YEARS OLD

45 YEARS OLD



19 YEARS OLD

MOUNT VERNON LADIES' ASSOCIATION (*dentures*)

Creating the three faces did not mark the end of the process. The skin under the chin and on the neck had to be tightened for the 45-year-old and much more so for the 19-year-old. The heads were ready. Now we had to reconstruct the bodies. Then we could digitally join them.

Constructing the Body

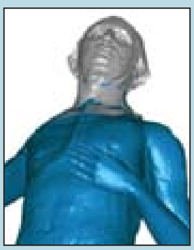
BOTH THE STATUE AND THE PAINTINGS portrayed a form somewhat different from what we expect to see in a 20th- or 21st-century male physique. I discovered that in keeping with an 18th-century custom common among English families of status, Washington's body had been corseted until about the age of five. I have not been able to find an example or even description of such a corset, but it would have differed from that used on girls and women to pull in the waist, because the effect altered the male body to look like a ballet dancer's. The shoulders were pulled back, puffing out the chest and flattening the area across the shoulder blades, as well as down, creating a long slope from the neck on each side; the natural inward curvature of the lower back was further accentuated, which then pushed the belly out. (As I also learned, Washington had been a fabulous ballroom dancer. In fact, he kept meticulous notes on each type of dance.) Once the growth trajectory of the body had been changed in the boy, the new shape would have persisted throughout life, which is why portraits of 18th-century English gentlemen, including the signers of the Declaration of Independence, have a distinctly different look to them than portraits of important men of later centuries.

Washington's unusual height for his day—probably 6′ 2″ (but not 6′ 3.5″, as sometimes cited; this is most likely the length of his coffin)—has been given as a reason for his uncommon ability not only as a dancer but also as a horseman.

RE-CREATING THE BODY

America's founding father at 19 was tall, muscular and lean. When the figure, which is shown here at its full length for the first time, is installed at Mount Vernon in the fall of 2006, it will be clothed in the apparel Washington would have worn as frontier surveyor. His auburn hair will be tied back in a ponytail.

Washington's height comes most reliably from Houdon's 1785 statue (*left*), which shows the president as at least 6' 2". The portraits are less reliable; Stuart's famous full-length painting (*right*), for example, contains bits of Washington and bits of other models



Attaching the head to the body required painstaking digital "stitching": the edges of the two parts are made up of many small triangles rather than being a smooth cut, so that joining them was like putting together a delicate jigsaw puzzle

Clothing from the collection at Mount Vernon showed that Washington, though still unusually thin, was slightly heavier than the statue portrays him

Washington's body had been corseted until about the age of five, pulling back the shoulders, puffing out the chest and creating a long slope from the neck down to the shoulders

19 YEARS OLD

Trumbull's 1797 painting gives further evidence of Washington's long legs, which, it was said, he could wrap around the belly of his horse (Washington is on a dark horse at the middle right)

45 YEARS OLD (astride a horse)

57 YEARS OLD

LIBRARY OF VIRGINIA (*Houdon sculpture*); NATIONAL PORTRAIT GALLERY, SMITHSONIAN INSTITUTION/ART RESOURCE, NY (*Lansdowne portrait*); GAVIN ASHWORTH (*suit*); ARCHITECT OF THE CAPITOL (*Trumbull painting*)

In keeping with an 18th-century custom, Washington's body had been corseted until about the age of five.

He was described as wrapping his long legs tightly around his horse's belly as he outrode his comrades. As I found, Washington could do that not only because he had long legs but also because many of the breeds of horses kept in the 18th century were smaller than most of those developed during the 19th century. Another reason—based, it turns out, on only one much-repeated incorrect description—is that Washington was supposed to have been very broad across the hips, which, in turn, explained why he was able to sit so well in the saddle.

To find more concrete information about Washington's physique, I asked the curators at Mount Vernon for an array of items he might have worn; the style of clothing at the time was formfitting, especially around the torso, hips and legs. But I had to whittle my wish list down quickly. No hats, shoes, boots or gloves existed—items that would have provided details on the size and shape of head, hands and feet. Collections at Mount Vernon and other museums, however, contained clothing from the 1770s through the 1790s (his middle to late years) that could be verified as having been worn by Washington and not altered after his death to fit relatives. Aided by the expert eye of Linda Baumgarten, curator of textiles at Colonial Williamsburg, I then obtained linear and volumetric measurements on Washington's clothing and compared them with the Houdon statue.

These comparisons proved critical when I studied the statue, which stands in the state capitol building in Richmond, Va. As I approached it for the first time, I immediately saw that Washington appeared much thinner, particularly around the hips, than descriptions and portraits portrayed him. With PRISM's Gene Cooper and Scott Van Note, I compared the lengths of the arms and legs and the width between the shoulders of the statue with the measurements from the clothing. They were almost identical, although the clothing indicated a somewhat bulkier individual than the statue represented. Not tremendously bulkier, but a few centimeters one way or another does make a difference. We digitally adjusted the shape of the statue accordingly. From there, I could reconstruct the bodies of the 19-, 45- and 57-year-olds, guided by general knowledge about how bodies change with age and by some information specific to the man himself.

Historical documents suggesting that Washington was lanky in his older years—no doubt because of bouts of serious illness and difficulty eating—corroborated the measurements from the clothing, so I thought it reasonable to use the adjusted body of the statue for the 57-year-old figure. The 45-year-old body required a different approach. The elder Peale's portraits of Washington at 40 and 47 show the general as heavier around the belly and hips than later portraits and the clothing indicate. But why would he be heavier, I wondered, especially because, by the age of 47, he had endured the hardships of war, including the winter at Valley Forge. His dental pain during those years was so unremitting that he may have changed his diet to softer foods that were probably higher in fat content. (Washington was in such agony during the battle of Trenton in 1776—he was 44—that his physician commissioned a blacksmith to forge a set of pliers so he could remove the offending tooth.) Thus, I made the 45-year-old body bulkier, especially around the middle. As for the 19-year-old, even if he had come close to his full adult height, he would not have been hormonally mature. He would have been fit as a result of carrying his surveying equipment uphill and down, but he would have been thin and sinewy, and this is how I portray him.

Finally, we could put the heads on the bodies. To do this, we had to digitally stitch together scans of each head and body. The scans produce data points that are connected to form triangles, so it was like piecing together a jigsaw puzzle of thousands of small polygons. We then sent the digital data to Kreysler and Associates in northern California to use in milling the heads of the three different Washingtons from dense plastic foam.

These traveled across the country to Studio EIS in New York City, where molds were made so the heads could be formed in clay. They will eventually be attached—on the basis of our digital "jigsaw"—to bodies made at the studio. The bodies will be constructed of dense foam covered with plaster and padded where necessary to simulate the softness of a real body. I worked with sculptor Stuart Williamson, a consultant at EIS, to give each face a unique expression before the clay itself was molded to create wax reproductions. Sue Day, an artist also working as a consultant at the studio, has painted these wax faces to look extremely lifelike, down to the pale skin with ruddy cheeks and grayish-blue eyes that Gilbert Stuart described for Washington. Reddish hair will be implanted in the younger two and tied back in the wiglike fashion of the time; the 57-year-old will have grayish hair to simulate the powdered look he would have had for the inauguration scene.

In the end, I hope each of the three representations of the father of this country will impart something of the dynamic and human side of a person who, despite his historical importance, remains a colorless figure to most Americans. Beyond this, another lasting result of the project is that through novel collaborations and applications of different research domains, my collaborators and I have made inroads into fusing science, art and history in ways that were hardly imaginable even a few years ago. SA

MORE TO EXPLORE

George and Martha Washington: Portraits from the Presidential Years. Ellen G. Miles. Smithsonian Institution, National Portrait Gallery, 1999. Exhibition Web site: **www.npg.si.edu/exh/gw/**

His Excellency: George Washington. Joseph J. Ellis. Vintage, 2005.

1776. David McCullough. Simon & Schuster, 2005.

Skeleton Keys: An Introduction to Human Skeletal Morphology, Development, and Analysis. Second revised edition. Jeffrey H. Schwartz. Oxford University Press (in press).

The Mount Vernon Web site: **www.mountvernon.org**

LEVEES

Into the Breach

Hurricane Katrina hit Louisiana on early Monday morning, August 29, 2005, and by Monday night levees and flood walls were bursting across New Orleans. Since then, four teams have investigated what happened.

The American Society of Civil Engineers (ASCE) inspection team was led by Peter G. Nicholson, a civil and environmental engineer at the University of Hawaii at Manoa. In his November 2 testimony to the U.S. Senate, Nicholson said his group observed "a number of different failure mechanisms" that led to "dozens of breaches" throughout the levee system.

The three most common failure modes [*see illustrations*] are similar for big earthen levees along rivers and lakes and for concrete flood walls along shipping and drainage canals. The mechanisms have caused the majority of levee failures worldwide; one way or another, water weakens the barrier's base until the barrier topples or collapses.

A robust foundation is key. Levees are needed in floodplains, where soils tend to be wet and can change every 100 yards along a proposed route. The exact path chosen "depends on which types of soil are where, their strength," and local water pressure, notes Francisco Silva-Tulla, a soil mechanics consultant in Boston who is on the ASCE team.

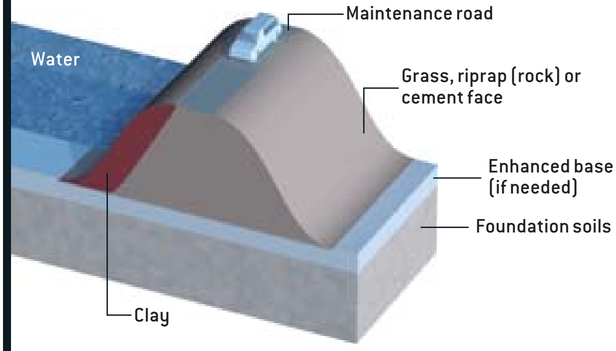
Building begins after field surveys and borings characterize the soils. Engineers then typically dig out shallow trenches or pits along the path to obtain earth for the levee. Their biggest concerns are preventing seepage under or through the embankment, stabilizing the slopes, and overbuilding to counteract settling, which can be up to 5 percent for soils compacted during construction and 15 percent for uncompacted material. New levees must usually settle for one to two years before the surface is finished.

A levee's height, the depth of its foundation or pilings, the quality of its materials, the degree of compaction (done by driving heavy machinery over the layers), and the type of slope finish depend greatly on the money approved for a project. When finalized, the investigation reports will clarify whether bad design, improper construction or simple failure to erect sufficiently large levees drowned New Orleans and the Gulf Coast.

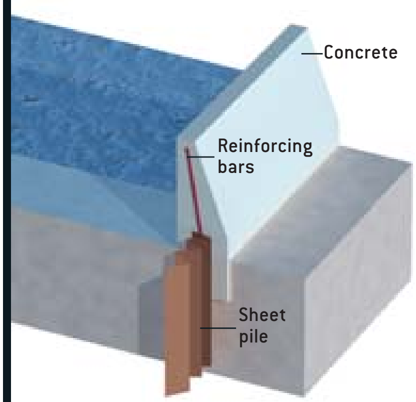
—Mark Fischetti

LEVEES are earthen embankments. Sandy soils are strong but are permeable to water; clays are weaker but are more impervious to water. Although designs vary widely, ideally strong soil forms the foundation and clay lines the water side. Slopes are finished with grass, riprap (rock) or soil cement, each of which, respectively, provides increasing protection against erosion.

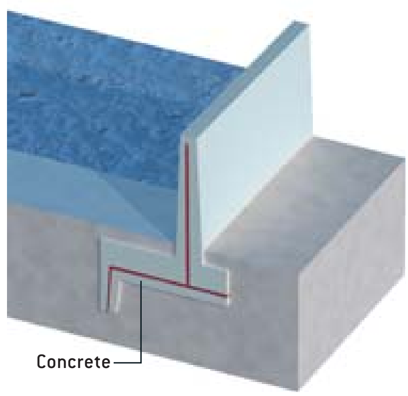
STANDARD LEVEE



I-WALL



INVERTED T-WALL



BRYAN CHRISTIE DESIGN

FLOOD WALLS may be built directly along canals or atop levees to add height when there is no space to enlarge them. I-walls are anchored by steel sheet piling. Inverted T-walls are anchored with a concrete footing that can provide greater resistance to lateral forces and reduce foundation erosion. I-walls failed much more frequently than T-walls did in New Orleans.

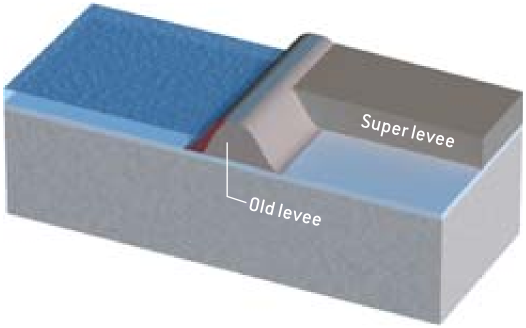
DID YOU KNOW...

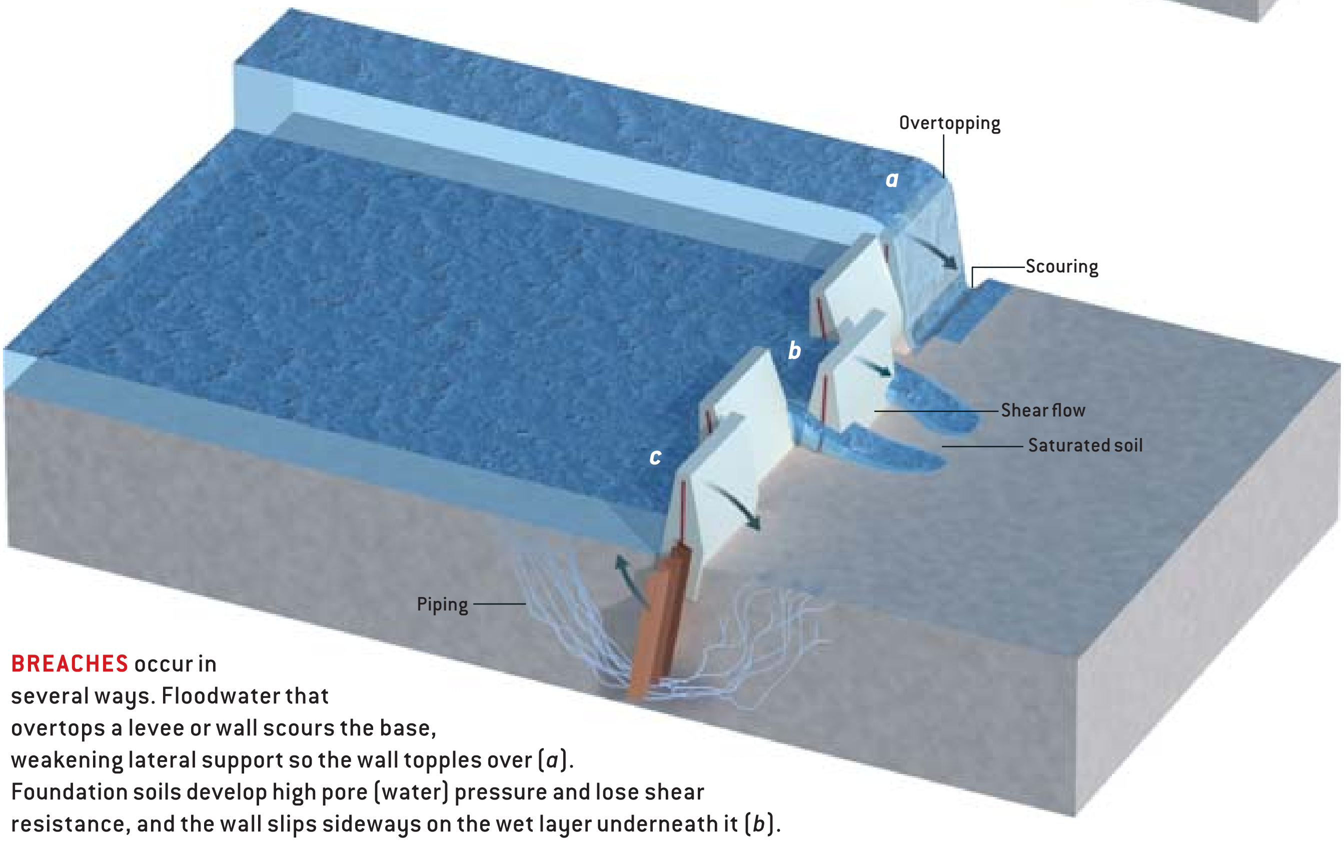
▯ LIQUEFACTION: Earthquakes can shake a levee loose, especially if the foundation is sandy or silty and becomes waterlogged. The tremors liquefy the soggy layer like a blender, and the levee or wall can surf laterally for tens of yards, tearing the structure apart.

▯ TRANSITION ISSUES: A number of breaches in New Orleans occurred where an earthen levee met a concrete flood wall and rising water scoured the joint and pushed through. "Transitions are a big problem; they are weak points," says ASCE team member Francisco Silva-Tulla. Transitions commonly occur when levees meet flood walls, floodgates, bridge abutments, or a different levee design and benefit from extra strengthening.

▯ EARLY WARNING: If maintenance crews and emergency officials knew a section of levee was weak, they could shore it up or order timely evacuations. Kane GeoTech in Stockton, Calif., has wired several "smart levees" on Tyler Island, part of the Sacramento River Delta in California. Piezometers, which measure water pressure, are inserted on the river side and inside the levee at its center line and landward toe. Coaxial cable sensors are also laid. All the instruments lead to a computer at an exposed meter box; a technician can read the data, or it can be broadcast. Readings can be taken every few minutes. Changes in piezometer pressure indicate possible piping (*see "Breaches" diagram below*), and coaxial sensors can tell if a levee is beginning to shift; either can presage a breach.

SUPERLEVEES offer superior protection. They are being built in Japan to shore up conventional levees that might shake apart during an earthquake. They are so wide (30 times the levee height) that many existing buildings have to be demolished to make room—unless a storm has already cleared the way.





BREACHES occur in several ways. Floodwater that overtops a levee or wall scours the base, weakening lateral support so the wall topples over (*a*). Foundation soils develop high pore (water) pressure and lose shear resistance, and the wall slips sideways on the wet layer underneath it (*b*). Seepage driven by high water pressure creates "pipes" in erodable soil that tunnel below the wall, undermining the foundation so the wall collapses (*c*).

Have a topic idea?
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My Virtual War

A DISTURBING STROLL THROUGH A SIMULATED BATTLEFIELD **BY MARK ALPERT**

War is hell. William T. Sherman, the Civil War general, made this statement back in 1880, but it's just as true today. The current conflict in Iraq, now almost three years old, is confronting American soldiers with horrors that we on the home front can only guess at. Recently, however, I got a high-tech glimpse of what the grunts in Iraq must be going through. During a visit to the U.S. Naval Research Laboratory (NRL) in Washington, D.C., I immersed myself in several virtual-reality training systems that can simulate urban combat with uncanny realism by allowing users to walk, march and run inside an electronic battlefield.

COMBAT TRAINING SYSTEM allows users to traverse a virtual battlefield and confront computer-generated enemies. Viewed on a head-mounted display, the simulated landscape shifts and pivots realistically as the user walks and turns.

The Office of Naval Research is developing these systems as part of a six-year, $40-million program called Virtual Technologies and Environments (VIRTE). Much of the work focuses on the needs of the Marine Corps, which is engaged in some of the bloodiest fighting in Iraq. My first stop at NRL was a small windowless room containing the VirtuSphere, a nine-foot-high hollow ball made of sturdy perforated plastic. The VirtuSphere rests on 26 wheels rising from a stationary platform; the wheels allow the sphere to rotate in place like a giant trackball, turning in any direction. Next to the sphere was its Russian co-inventor, Nurakhmed Latypov, whose company—also named VirtuSphere—is working with VIRTE to incorporate this contraption into a training system.

Latypov gave me a demonstration. He opened the VirtuSphere's hatch, stepped inside and began running full-tilt like a hamster in an exercise wheel. As the sphere turns, two tracking devices fire ultrasound beams at it from below and measure the Doppler shift of the echoes to determine the speed and direction of its spin. This information goes into a virtual-reality program running on a nearby computer, which calculates what the path of the user would be if he or she were traveling through a simulated landscape instead of scrambling inside the VirtuSphere. The user wears virtual-reality goggles that display the landscape, which advances and recedes as the person moves about. (The system transmits the signal wirelessly to the head-mounted display through the VirtuSphere's perforated shell.) The goggles have accelerometers and magnetometers to detect changes in the orientation of the user's head—if the individual turns left, right, up or down, his or her view of the virtual world pivots accordingly.

The marines are interested in the VirtuSphere because real-life combat training facilities are expensive and often impractical, especially at temporary bases overseas. The VirtuSphere, in contrast, can be taken to the front lines or onboard ships and assembled in a few hours. Conducting maneuvers in the device, however, takes a little practice. When I entered the VirtuSphere, I had trouble keeping my balance. Although it was relatively easy to start walking and change direction, it was harder to slow down and stop. At one point I took a step backward and went tumbling. Still, after a few minutes I felt confident enough to don the head-mounted display and begin my virtual trek.

The first program I tried was a three-dimensional rendering of a proposed sports center to be built in Moscow. (Latypov had previously used the program to assist Moscow's bid for the 2012 Olympics.) In fits and starts, my feet turned the VirtuSphere, propelling me up the stairways and down the corridors of this weirdly barren virtual building. I came to a long hallway lined with identical doors that opened automatically when I approached. "I hope this isn't the

COURTESY OF THE OFFICE OF NAVAL RESEARCH women's room," I said as I walked through one of the doorways, but the room was empty.

I finally reached an indoor swimming pool, where I encountered a surprise: animated monsters that looked vaguely like bugs and robots. I was supposed to shoot the monsters using a handheld controller, but I still felt a little unsteady. Perhaps sensing my ineptitude, the program generated a second shooter who appeared on my display as a flickering soldier. As I tried to get out of the line of fire, I heard a shot. I spun around and saw a splatter of blood on the floor. Although the program's graphics were no more sophisticated than those of an ordinary computer game, the simulated violence seemed much more intense and confusing because I couldn't see everything at once. By the time I ended the program and stepped out of the sphere, I was sweating copiously.

The VirtuSphere is not the only device that allows users to walk inside a virtual world. Because the goal of VIRTE is to develop and evaluate a mix of technologies, an NRL group led by Jim Templeman is working on a system called Gaiter that extrapolates the path of a user in a completely different way. To enter Gaiter, I strapped on a head-mounted display and a flak jacket, as well as forearm and shin guards. All these accessories, plus a model rifle, were tagged with retroreflectors, which can reflect a beam of radiation back to its source regardless of the angle of incidence. Then I was tethered to a harness dangling from the ceiling.

Surrounding me were 10 high-speed cameras that emitted beams of infrared light and captured the reflections. By tracking the motion of my shin guards, the Gaiter system measured my gait—the length and rate of my steps—as I walked in place, lifting my feet up and down. This measurement determined how quickly I moved in the virtual world; if I stepped high and fast, I could zoom across the simulated landscape. I was immersed in a different program now, a reproduction of an actual urban-combat training site at Fort Benning, Ga. I took a virtual stroll past several blocky, brightly colored buildings. When I pointed my rifle or extended my arms, I could see their animated duplicates on the display. I could even knock down simulated chairs or tables in my path.

VIRTUSPHERE rotates in place as the user inside moves about. From the sphere's motions, a computer calculates the user's path in the simulated world.

COURTESY OF VirtuSphere

The major drawback of these systems is their expense. The VirtuSphere, for example, costs between $50,000 and $100,000. (The company hopes to sell an entertainment version to arcades for $20,000.) Cheaper, simpler platforms may suffice for virtual exercises involving large numbers of marines. NRL neuroscientist Roy Stripling is developing a system, informally called Pod 1, that has no complex mechanism for incorporating locomotion—you just press a switch on the rifle's barrel to move back and forth in the virtual world—yet it provides a very lifelike simulation by accurately tracking the twists and turns of the user's torso, head and rifle, which are all marked by red LEDs and monitored by an array of cameras.

Using this system to navigate the Fort Benning program, I managed to enter one of the blocky buildings, climb the stairs to the second floor and stumble into a firefight with the enemy, a squad of computer-generated thugs. In real life I would've been cut to pieces, but the program was set to God mode, making me impervious to their bullets. I closed in on my opponents and shot them point-blank. But when I tried to leave the building, I couldn't find the stairway in the maze of dark rooms now littered with virtual corpses. I was just about to panic when K. C. Pfluger, a marine reservist and independent contractor, said, "Don't worry, I'll get you." He slipped on a pair of goggles and entered the simulation; moments later his avatar—a grunt in camouflage—appeared on my display and led me downstairs.

By this point I was suffering from simulation sickness, an awful nausea induced by too much virtual reality. The NRL researchers had told me that the experience would give me an appreciation for the rigors of combat, and they were right: I felt a small slice of the fear and a fair amount of the exhaustion. But most of all, I was repelled. Even a virtual war can look ugly and futile. No matter how many simulated opponents you kill, they keep on coming, one after another, an inexhaustible enemy, and the program doesn't end until you take the goggles off. SA

A Tour of Turing

THE LIFE AND DEATH OF ALAN TURING CONTINUE TO OFFER UP MYSTERIES **BY ANDREW HODGES**

THE MAN WHO KNEW TOO MUCH: ALAN TURING AND THE INVENTION OF THE COMPUTER
by David Leavitt
The Great Discoveries Series.
W. W. Norton, 2005 ($22.95)

Twenty-five years ago the word "Turing" tingled with mystery for the few who knew it. Readers of Douglas Hofstadter learned that Alan Turing belonged with Gödel in exploring minds and logic and knew also of "the Turing test" for artificial intelligence. But others were aware of Turing as a British figure, a Cambridge mathematician, emerging in connection with the huge World War II operation to break the Enigma ciphers. His crucial importance in the battle of the Atlantic was still shrouded by state secrecy. In fact, it was only after this secrecy was lifted that he began to be acknowledged for another great contribution—his role in the origin of the computer.

The conspicuously missing feature was the testimony of Alan Turing himself. He had died at age 41 in 1954, apparently killing himself with cyanide—and leaving a jagged hole in history. By 1980 rumor told of the prosecution and punishment that he had undergone as a homosexual in 1952. But even then, such a story could no longer serve as a simple explanation of suicide. Turing's friends had known him as unashamed and contemptuous of convention. A different suspicion struck those who knew the dark side of the 1950s. The victorious Allies must have been appalled by this revelation of the man who knew their secrets: How could Turing's private desires be reconciled with the public demands of state security? But on this question, total silence reigned.

Since then, the situation has completely changed. A number of events have made Turing's life better known to the public than that of probably any other mathematician. A notable actor, Derek Jacobi, has played Turing's drama to millions of viewers in Hugh Whitemore's 1986 play *Breaking the Code*. Little is secret from Google, and computer science students may find themselves expected to assess his life and death. Massive U.S. government releases in the 1990s have made World War II code breaking the subject of detailed scholarship, and conferences and books celebrate Turing's continuing influence. Complexity theory and quantum computing build on his analysis of computation, and since the 1980s Roger Penrose has given new life to Turing's deepest questions. Above all, Turing's reputation is now solidly underpinned by the vindication of his vision. Although John von Neumann led by a few months in creating a computer plan, it was Turing who explained in 1946 how "every known process" could be turned into computer software. Turing had seen this prospect in the simple but revolutionary principle of his Universal Turing Machine, laid out in a paper in 1936, and had thus created an amazing link between the purest mathematics and the most productive industrial applications.

But there are always more secrets to unravel and always room for yet another

ALAN TURING (*at far left*) in 1946 with members of his running club near the London laboratory where he worked on his computer design.

introduction. A series of "great discoveries," such as the current undertaking from W. W. Norton, cannot ignore Turing, and it is interesting to see the story of his contributions attempted by an American novelist, David Leavitt. The story is not simply a question of dates and facts. To use one of Turing's own images, it is like the skin of an onion. It calls for a writer who can unpeel it with care and who is unafraid of tears.

Intensely private, yet relishing popular writing and broadcasts, fiercely proud and yet absurdly self-effacing, Turing led a strange life intertwined with characteristically odd British puzzles of class and lifestyle. A central paradox is that he asserted the "heretical theory" that the human mind could be rivaled by a computer, whereas his own personality so little resembled the output of a machine. It was willful, individualistic, unpredictable. His struggle to incorporate initiative and creativity in his artificial-intelligence theory is therefore a personal drama. This is a puzzle that goes to the heart of science and yet is also fine material for a novelist of insight.

Leavitt's focus is elsewhere, however. It is on Turing as the gay outsider, driven to his death. No opportunity is lost to highlight this subtext. When Turing quips about the principle of "fair play for machines," Leavitt sees a plea for homosexual equality. It is quite right to convey his profound alienation and to bring out the consistency of his English liberalism. It is valuable to show human diversity lying at the center of scientific inquiry. But Leavitt's laborious decoding understates the constant dialogue between subjective individual vision and the collective work of mathematics and science, with its ideal of objectivity, to which Turing gave his life.

Scientific content is not neglected; Leavitt's discussion of Turing's 1936 paper has perhaps excessive technical detail. But the vision is partial: he fails to give any discussion of what Turing's proof implies for the question of artificial intelligence. A general problem is that, being the prisoner of secondary sources, the author finds himself the outsider. He quotes from another writer on statistical methods in 19th-century code breaking but omits the primary fact that Turing's central scientific contribution at Bletchley Park, the British wartime cryptanalytic center, was his statistical theory of weighing evidence. The book's subtitle is "Alan Turing and the Invention of the Computer," but on the critical question of Turing's relationship with von Neumann it must rely on quoting Martin Davis's *Engines of Logic*.

This is no groundbreaking book, nor does it do much hoeing or weeding. It is a survey of a field long cultivated by other hands, devoid of new witnesses. The title, also secondhand, suggests new light on his death, but there are no new facts. Leavitt claims a "sad descent into grief and madness" induced by the prosecution—he ignores the heap of manuscripts from Turing's last prolific year of research and misrepresents his renewed interest in physics as ravings. No new revelation about Turing's code breaking is offered. Leavitt describes his visit to Bletchley Park—now a museum—but only as a tourist, to report the embarrassment of a tour guide in describing Turing's fate. In this book, Leavitt offers his own tour. It is one that many will find congenial and that will at least introduce new readers to the still tingling enigma of Alan Turing. SA

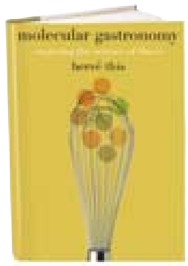
Andrew Hodges, a mathematician at the University of Oxford, is author of Alan Turing: The Enigma *(1983).*

THE EDITORS **RECOMMEND**

MOLECULAR GASTRONOMY: EXPLORING THE SCIENCE OF FLAVOR

by Hervé This. Columbia University Press, 2006 ($29.95)

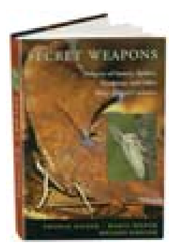
A well-known chemist, a popular French television personality, a best-selling cookbook author, the first person to hold a doctorate in molecular gastronomy, and, coincidentally, a former editor at *Pour la Science,* the French edition of *Scientific American.* All these appellations come together in Hervé This, a scholar-gastronome who now has his first book available in English. One of the founders of molecular gastronomy, which brings the instruments and experimental techniques of the lab into the kitchen, the author blends practical tips and provocative suggestions with serious discussions—about how the brain perceives tastes, for example, and how chewing affects food.



SECRET WEAPONS: DEFENSES OF INSECTS, SPIDERS, SCORPIONS, AND OTHER MANY-LEGGED CREATURES

by Thomas Eisner, Maria Eisner and Melody Siegler. Harvard University Press, 2005 ($29.95)

"Defense is at the root of the evolutionary success of arthropods." And what a panoply of defenses they display. The authors—Thomas Eisner is J. G. Schurman Professor of Chemical Ecology at Cornell University; his wife, Maria Eisner, a research associate of biology at Cornell; and Melody Siegler, an associate professor of biology at Emory University—present 69 examples. They range from *Mastigoproctus giganteus* (the vinegaroon, which ejects a spray with an acetic acid content of 84 percent when it is physically disturbed) to *Apis mellifera* (the honeybee, whose stinger produces a chemically complex venom made up of about half mellitin, which is largely responsible for the pain associated with a bee sting). Yet with all that is known on this subject, much must remain to be discovered because millions of arthropod species are thought to be undiscovered. "Think of what this means," the authors say, "in terms of biological wonders lying in wait, in terms of new bugs and bug adaptations awaiting discovery."



Bait and Switch

SOME NOTES ON OUR FEATHERED AND FINNED FRIENDS **BY STEVE MIRSKY**

On Thanksgiving Day, I saw a bird get stuffed. The bird was a great blue heron, *Ardea herodias,* at the Loxahatchee National Wildlife Refuge in Boynton Beach, Fla. Just after noon, the heron fired its beak into floating vegetation in a canal. He came up with a face full of foliage in the midst of which was a honking big catfish. The avian epicure thus grabbed both the salad and the sushi courses in one swell swoop.

The great blue then flew perhaps 75 yards to a sandbar, where he dropped his takeout—and checked on the state of another large fish he had apparently already caught and deposited there. (I found Web references attesting to the fact that great blues occasionally catch two fish at the same time, putting the kibosh on my claim to a bona fide scientific discovery. So, unfortunately for everyone, it's back to basement chemistry experiments.)

Great blue herons work on large prey for quite a while before the final big gulp. They repeatedly impale the fish with their beaks to soften them up, dip them in water to wet them down and orient them so that they'll slide in headfirst. Our *Ardea* alternated his attention between his two fish. Despite the holiday, there weren't any turkeys at the refuge, but a few turkey vultures did arrive to see about getting a piece of the action. The heron tried to guard both his catches but ultimately gave up his first fish to the vultures to concentrate on the fresher catfish. After almost an hour, the bird picked up his traumatically tenderized, properly positioned prize and swallowed it whole. I then went to my dad's house and pigged out, with no egrets.

In another fish tale, Vermonters got a rude surprise just after Thanksgiving. Lake Champlain sea lampreys, which chow down on tasty salmon and trout before humans can, had been "the lead villains on Vermont's 'Most Unwanted' list of invasive species," according to the *Burlington Free Press*. But genetic analysis revealed that the lamprey is in fact a Vermont native. Well, native enough—they probably got caught in the then new lake some 11,500 years ago.

The development is a particular blow to the psyche of the locals, who vaunt Vermontitude. An oft-told story concerns a Vermont couple who travel to a hospital just over the border in New Hampshire, where the wife gives birth. The next day they return home with their baby son. The boy never leaves the state again, becomes an honored citizen and passes away peacefully in his late 90s. The newspaper headlines his obituary: "New Hampshire Man Dies in Vermont."

Finally, news about the one that got away. Idaho Senator Larry Craig had a bone to pick with what's called the Fish Passage Center in Portland, Ore. According to the *Washington Post,* the center's fish counts showed that the Columbia-Snake hydroelectric system was killing salmon. And that spilling some of the water over dams rather than through turbines would buoy salmon numbers. A judge then tipped the scales in favor of the fish, but that meant utilities would take it on the chinook.

So Senator Craig—a former National Hydropower Association "legislator of the year"—then added a few words to a piece of $30-billion general legislation that simply ended the center's $1.3-million annual funding. He seized on a 2003 independent assessment of the center, which indeed did have a few criticisms. The *Post* quoted an author of the review, however, as saying that the center's work was of high technical quality and that Craig's selective quoting from the report gave a misleading impression of the reviewer's generally good opinion.

"False science leads people to false choices," Craig accurately said in defending his efforts. And no science leads to no choices. The senator's press secretary answered a reporter's question by saying that Craig wasn't being vindictive, because "that is not his style." The secretary's name, deliciously, is Whiting, speaking of fish stories. SA

ILLUSTRATION BY MATT COLLINS; PHOTOGRAPH BY FRANK VERONSKY

ASK THE EXPERTS

What causes a fever?

Peter Nalin, a physician and associate professor of clinical family medicine and director of the family practice residency program at Indiana University, explains:

Fever—an elevated body temperature—is usually related to stimulation of the body's immune system. (Normal temperature fluctuates from about one degree below 98.6 degrees Fahrenheit to one degree above that number.)

Fever can support the immune system's attempt to gain advantage over infectious agents, and it makes the body less favorable as a host for replicating viruses and bacteria, which are temperature sensitive.

Infection is not the only cause, however. Amphetamine abuse and alcohol withdrawal can both elicit high temperatures, for example. And environmental stresses can also play a role in heatstroke and related illnesses.

The hypothalamus, which sits at the base of the brain, acts as the body's thermostat. It is triggered by floating biochemical substances called pyrogens, which flow through the bloodstream from sites where the immune system has identified potential trouble. Body tissue makes some pyrogens; many pathogens also produce them. When the hypothalamus detects the chemicals, it tells the body to generate more heat by increasing metabolism and to retain that warmth by reducing peripheral blood flow—thus producing a fever. Children typically get higher fevers that occur more readily, reflecting the effects of pyrogens on an inexperienced immune system.

"Feed a cold, starve a fever." Should a feverish person eat little or nothing, as the saying suggests? Yes. During fever, all the body's functions are occurring amid increased physiological stress. Provoking digestion during such physiological stress overstimulates the parasympathetic nervous system when the sympathetic nervous system is already active. As a result, it is possible that during a fever the body could misinterpret some substances absorbed from the gut as allergens. Finally, excessive fever can, on rare occasions, trigger seizures, collapse and delirium—all of which may be further complicated by recent eating.

Sometimes fever can climb too high for the body's own good. Temperatures exceeding 105 degrees F, for instance, can threaten the integrity and function of vital proteins. Cellular stress, infarction (heart attack), tissue necrosis, seizures and delirium are among the potential consequences. If a fever outpaces the body's own temperature-reduction mechanisms, "cooling blankets" or other methods can help.

Why do we put salt on icy surfaces in the winter?

—T. Stadfelt, Huntington Beach, Calif.

The late John Margrave, a chemistry professor at Rice University, provided this answer:

In short: salt makes the ice melt.

All ice-covered areas in fact have small puddles of water. Applied to such surfaces, the salt dissolves. Liquid water has what is known as a high dielectric constant, which allows the salt's ions (positively charged sodium and negatively charged chlorine) to separate. These ions, in turn, hydrate—that is, they join to water molecules. This process gives off heat, which in turn melts microscopic parts of the ice surface. Thus, a substantial amount of salt spread over a large surface can thaw the ice. And as automobiles roll along, the pressure helps to force the salt into the ice, and so more hydration occurs.

Much of the rock salt applied in the winter is the same substance that comes out of your saltshaker. The only difference is that rock salt has crystallized in larger pieces, whereas table salt is ground to a more or less uniform size. Calcium chloride, manufactured from brines and other natural materials, is just as commonly used to melt ice on the streets as sodium chloride is. SA

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

MATT COLLINS