China's Smoky Air: The Impact on Children (*page 72*)

SCIENTIFIC AMERICAN

What Causes MIGRAINES
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Running Out of WATER

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Solar Storms
How the Sun Could Damage Power Grids

No-Fog Glass
Self-Cleaning Windows Steal Nature's Secret

Answers from Atoms
Practical Quantum Computing with Ions

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SCIENTIFIC AMERICAN August 2008 ▪ Volume 299 Number 2

PUBLIC HEALTH

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By Dan Fagin

Epidemiologists find molecular clues to air pollution's impact on youngsters. Routine use of screening technologies to measure such biomarkers could, at least theoretically, identify people at risk from specific pollutants.

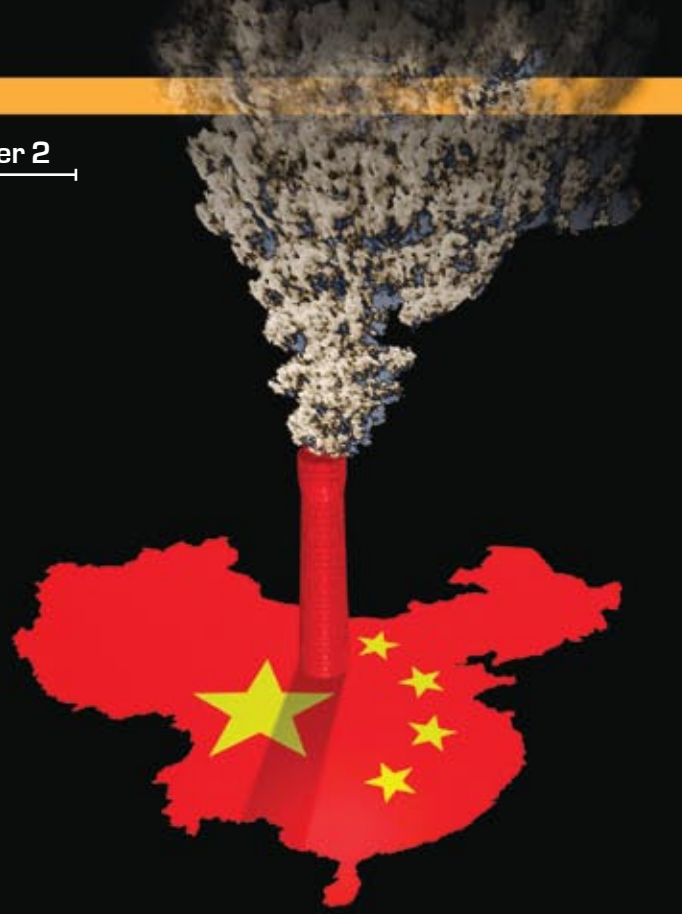

Image by Jean-Francois Podevin

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A recurrence of the 1859 solar superstorm would be a cosmic Katrina, causing billions of dollars of damage to satellites, power grids and radio communications.

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Will our thirst for freshwater squeeze the earth's resources dry? Image by Cary Wolinsky.

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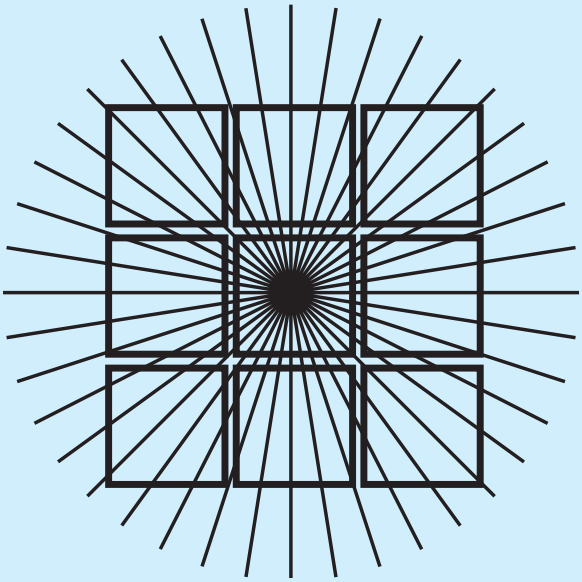
WHAT DICTIONARIES AND OPTICAL ILLUSIONS SAY ABOUT OUR BRAINS ▼

Cognitive scientist Mark Changizi is not interested in how the brain accomplishes a task but rather why it performs the function in the first place. More at **www.SciAm.com/aug2008**



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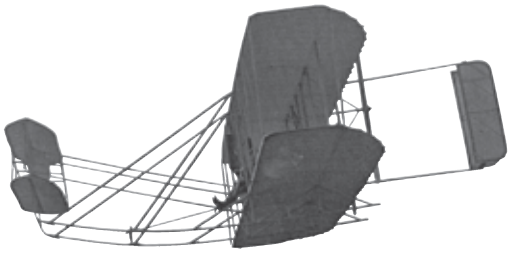

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Helping China

Aiding the earthquake victims should not distract from other challenges

Online associate editor David Biello arrived in China this past May with the intention of reporting for *Scientific American*'s Web site on the country's daunting environmental and health challenges. Those subjects suddenly redefined themselves on the afternoon of May 12, however, when a massive magnitude 7.9 Wenchuan earthquake tore apart Mianyang, Chengdu and other communities in the western province of Sichuan. Nearly 70,000 people were killed, and millions were abruptly left homeless.

Biello's reports on the tragedy, which are available at www.SciAm.com, describe some of the resulting chaos. In the wake of such disasters, the most desperate physical needs—for food, drinking water, sanitation, shelter and medicine—grab priority: efficiently addressing the needs of the hungry, injured and homeless has to be the focus of any aid. Unfortunately, such acute concerns can pull attention away from more persistent catastrophes brewing in the environment, and China will have an abundance of those long after the last traces of this recent quake's damage have been cleaned up. In its rush to industrialize and raise its economy, China has incurred nightmarish air and water pollution hazards, among other environmental burdens.

Journalist Dan Fagin writes about one such newly discovered problem in his article "China's Children of Smoke," beginning on page 72. As he reports, Frederica Perera, an investigator in the young field of molecular epidemiology, has found that in China, children born and raised under the clouds of smoke spewed by a coal-burning power plant have slightly smaller heads and lower scores on developmental tests than kids exposed to cleaner air do.

Fundamentally, China is on an earlier, dirtier segment of the economic development curve that all the industrial superpowers followed. In China, however—at least around the major cities—the transition back to a more benign environment is happening about twice as quickly as it did historically. Western nations were able to clean up in part because they outsourced their dirty industries to other countries. (Indeed, we Westerners should feel some responsibility for China's current woes because most of its polluting industries feed our demand.) China has its own version of outsourcing: its cities are getting cleaner because the factories are moving to more rural areas, where they affect fewer people.

Ultimately, China (and other rising nations) needs technologies for producing energy and goods with less pollution. The U.S. and Europe could and should do more to help developing countries get those technologies. For example, the U.S. has in effect stalled in its efforts to develop ways to burn coal more cleanly. Yet those technologies will be crucially important not just in the U.S. and China (where they might improve local environments) but globally, because "clean coal" power will be essential for controlling global warming. Working on cleaner coal may not have the humanitarian immediacy of helping earthquake victims, but it may someday save even more lives. ■

DIRTY POWER: Coal-fired plants such as this one provide more than 70 percent of China's electricity.

JOHN RENNIE
editor in chief

FLYNN LARSEN (*Rennie*); DAVID BIELLO (*China pollution*)

Among Our Contributors

DAVID W. DODICK is a neurologist at the Mayo Clinic in Arizona. He studies the central nervous system abnormalities behind migraine and other forms of headache.

DAN FAGIN is an associate professor of journalism and directs the Science, Health and Environmental Reporting Program at New York University. He is working on a book about the childhood cancer cluster in Toms River, N.J.

PETER FORBES is a science writer living in London. His 2006 book, *The Gecko's Foot,* explored a variety of biomimetic, or bioinspired, technologies.

CHRISTOPHER R. MONROE holds joint appointments as a physicist at the University of Maryland and a fellow at the Joint Quantum Institute at Maryland and the National Institute of Standards and Technology. He specializes in the electromagnetic, laser and quantum control of matter.

STEN F. ODENWALD is an astronomy professor at the Catholic University of America who works on the cosmic infrared background and space weather phenomenology. His passion for astronomy was kindled at age 11 by *The Outer Limits* TV show.

PETER ROGERS is Gordon McKay Professor of Environmental Engineering and professor of city and regional planning at Harvard University. He is a senior adviser to the Global Water Partnership, an organization devoted to improving global water-management practices.

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Doping in Sports ▪ Economics ▪ Plant Coloring

APRIL 2008

"We have reached the stage in our 'progress' where meaningful sporting contests between individuals are no longer possible."
—*Ted Park* CALIMESA, CALIF.

Defining the Line

"The Doping Dilemma," by Michael Shermer, suggests that the possible penalties of using artificial enhancements in sports should be made greater than the possible rewards. But it is impossible to determine what is and is not an unacceptable artificial enhancement. With advances in medicine, biology and even prosthetics, the broad gray line will only get wider and murkier. We have reached the stage in our "progress" where meaningful contests between individuals are no longer possible.

Ted Park
Calimesa, Calif.

SHERMER REPLIES: *Park has identified the hard problem in sports administration: where to draw the line to create unambiguous decisions about what is allowed in a world of ambiguous grays. The answer is not easy, but we have to draw that line somewhere. I was race director of Race Across America and executive director of the UltraMarathon Cycling Association for a seven-year period, and these gray-area issues came up constantly. I discovered that the most satisfying solution for everyone was open communication between athletes and management to create an agreed-on set of rules that would be clearly defined and strictly enforced.*

Environmental Economics?

Robert Nadeau argues in "The Economist Has No Clothes" [Forum] that, by using a discarded theory of physics, a founding school of economics caused all economists to ignore the environmental impact of their subsequent theories. Using physics in economics is reminiscent of trying to apply classical physics in subatomic mechanics. But when I have taught economics with texts from at least 15 years ago, they have imparted such ideas as the scarcity of resources; market failures resulting in spillover costs; taxation as a reallocation technique; the environmental effects of unconstrained pursuit of high GDP; inelastic supply of some resources; and the use of cost-benefit analysis in approaching such problems. I conclude that the writers of these texts escaped some time ago any limited visions of their forebears.

Harry R. Clements
Wichita, Kan.

NADEAU REPLIES: *Unscientific axiomatic assumptions became foundational to mainstream economic thought after the 19th-century creators of neoclassical economics substituted economic variables in the equations of a theory in physics. Because there was no basis for assuming that the economic variables were similar to the physical ones, this action is not comparable to failed efforts by classical physicists to explain subatomic mechanics. It was a wholesale abuse of a scientific theory by nonscientists.*

I must disagree that mainstream economists have escaped the effects of this abuse. Some theoretical work—such as game theory, nonlinear analyses and convex analysis—has challenged axiomatic assumptions in neoclassical economics. But all these theories are premised on the unscientific assumptions that market systems are closed and self-correcting and move toward optimal states of equilibrium. This problem is not an esoteric one without real-world consequences. Such unscientific assumptions are under-

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mining efforts to implement scientifically viable economic policies and programs that could prevent global warming's most disastrous impacts. And if we fail to realize this very soon, recent scientific research strongly suggests that our future will be rather bleak.

Sun and Shadow

In "The Color of Plants on Other Worlds," Nancy Y. Kiang describes how plants on a world orbiting a mature type M star might appear black from adaptation of their photosynthetic pigments to that light spectrum. But such a world's habitable zone would be so close to the star that it would have a strong chance of being tidally locked, so that one hemisphere would continually face the star. Surface plants would probably develop photosynthetic pigments only on their lighted side. Their shadowed side would tend to be gray or brown and considerably lighter. Discovery of another world's plant pigments may therefore depend on the angle between the sight line of a space telescope and the line between the world and the star it orbits.

James W. Scott
Wyckoff, N.J.

PHOTOSYNTHESIS on planets with parent stars dissimilar from our own could lead to flora of a strikingly different color.

KIANG REPLIES: *Scott raises some excellent, fun points. Even on Earth there is latitudinal adaptation—not so much in pigments to spectral variation in radiation as in a plant's shape to the sun's height in the sky. The conical shape of coniferous trees at high latitudes, for instance, is better at intercepting light at low solar elevation angles. So, on a tidally locked planet orbiting a type M star, we might see a longitudinal gradient in plant pigments as well as adaptations to fairly fixed elevation angles of the parent star. The first telescopic missions to obtain planetary spectra will not be able to resolve such gradients, but scientists could make use of variations observed from a planet's different faces to tease out more information about its surface.*

Coming through the Border

Thomas B. Cochran and Matthew G. McKinzie's description of the exercise where depleted uranium slugs were passed through U.S. ports in "Detecting Nuclear Smuggling" has confirmed what many have long known: radiation portal monitors provide little actual security. The situation is perhaps even worse than portrayed. Not only are the monitors not effective against uranium, but they also do not work against weapons-grade plutonium if one understands the basic physics required to shield it. And those physics are well known around the world.

Jack L. Parker
Retired Fellow
Los Alamos National Laboratory

ERRATA "Weapons Revealed," by Stuart F. Brown [Working Knowledge], reports incorrect specifications for American Science and Engineering's backscatter imaging device. Its scan time is eight seconds, its beam frequency is 1,212 gigahertz and its beam energy is 50,000 electron volts.

"The Color of Plants on Other Worlds," by Nancy Y. Kiang, incorrectly states that brown algae have phycobilin pigments. Certain carotenoid pigments give them their brown color. And in the box "Filtering Starlight," the Y axis should read "Photon Flux Density (photons per meter squared per second per micron)."

The illustration in "Wag the Dog," by Michael Shermer [Skeptic], should have depicted the dog in the green box wagging its tail to its right and the one in the red box wagging its tail to its left.

Letters to the Editor

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Letters may be edited for length and clarity. We regret that we cannot answer each one. Join the discussion of any article at www.SciAm.com/sciammag

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Ads Go Subliminal ▪ Wrights Soar ▪ Continents Connect

Compiled by Daniel C. Schlenoff

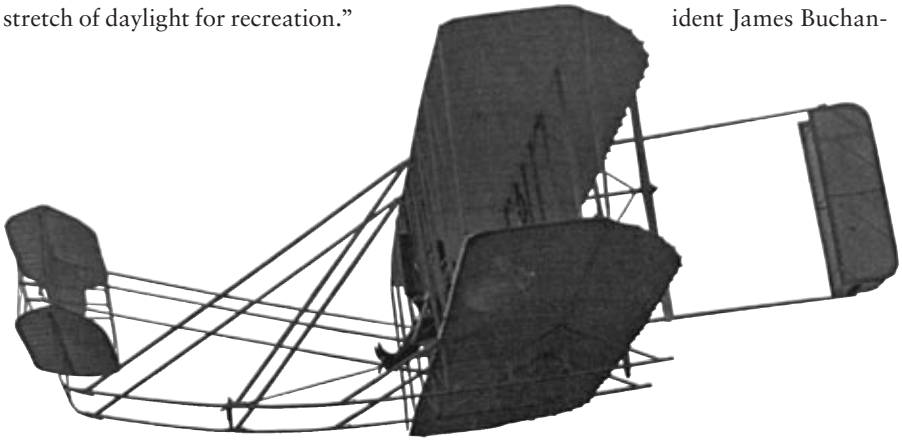
AUGUST 1958

BERYLLIUM—"The story of berylliosis is one of the most fascinating, contradictory, infuriating and controversial episodes in medical history. Some medical people argue even now that beryllium is incapable of causing disease. When one examines the clinical, biochemical and toxicological evidence, however, one cannot escape the fact that beryllium has caused at least 500 cases of poisoning in the U.S. alone during the past two decades. The story of beryllium highlights the whole problem of occupational disease in the present era. Advances in technology now develop so rapidly that the rare material of yesterday becomes the widely used material of today."

BUY THIS MAGAZINE—" 'Subliminal' stimulation has become a public issue since a commercial research firm announced that it can be used to sell popcorn and Coca-Cola to movie theater audiences. Last month three psychologists of the University of Michigan presented their views on the technology and ethics of subliminal advertising in *The American Psychologist*. The authors dismiss the theater test as vague and uncontrolled. They also point out that their code of ethics forbids using psychological techniques for 'devious purposes' and observe that through 'a kind of guilt by association' psychologists may come into disrepute because of the public revulsion against subliminal advertising."

AUGUST 1908

DAYLIGHT SAVINGS—"It is not often that a measure of such a startling character as the Daylight Saving Bill is introduced into the English House of Commons. The fact that the momentous changes advocated are proposed by William Willett, a member of the Royal Astronomical Society, suggests that the measure may not be so chimerical as might be supposed. It is proposed during part of the spring and autumn, and the whole of the summer, to advance the clocks throughout the country, with a view to including within the working hours a longer stretch of daylight. Among the commercial advantages are that large users of gas and other artificial light would realize a saving of $15,000,000. To the average individual, however, the most attractive feature of the proposed change is that it would afford a longer stretch of daylight for recreation."



WILBUR WRIGHT flying above the racetrack at Le Mans, France, 1908

WRIGHT FLYER—"In view of the fine performances of Wilbur Wright with his aeroplane in France, and also of the flights about to be made by Orville Wright near Washington, [D.C.,] at Fort Myer, we are glad to be able to present to our readers, in this issue, the first actual detail photographs of this world-renowned aeroplane which the Wright brothers have heretofore kept closely veiled from public view."

➥ The entire article from 1908 is available at **www.SciAm.com/aug2008**

AUGUST 1858

ATLANTIC TELEGRAPH—"On the evening of the 16th of August, the people of the United States were startled by the intelligence that Queen Victoria's message had been received. Crowds assembled around the bulletin boards, and the news spread like wildfire. Considerable disappointment was felt, however, in the first instance, caused by a portion only of the Queen's message being sent, but on the following day the succeeding paragraphs were received. The royal message began, 'To the President of the United States, Washington: The Queen desires to congratulate the President upon the successful completion of this great international work.' President James Buchanan included in his reply: 'May the Atlantic Telegraph, under the blessing of Heaven, prove to be a bond of perpetual peace and friendship between the kindred nations, and an instrument designed by Divine Providence to diffuse religion, civilization, liberty and law throughout the world.' "

[NOTE: The cable had severe technical problems and completely failed two months later.]

UP IN SMOKE—"The *Genie Industriel* says that it is difficult to account for the tremendous increase, during the last few years, of the consumption of tobacco in France: in 1830 the value of tobacco consumed was about $13,000,000. In 1840 it had increased to $19,000,000. In 1857 the sum of nearly $35,000,000 was puffed away in smoke."

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Genomic Exit ▪ Mind-Controlled Limbs ▪ Ad Hoc Networks ▪ Isolated Peoples

Edited by Philip Yam

Human Genome Head Resigns

On August 1, Francis S. Collins, the face of the Human Genome Project, was scheduled to have stepped down as director of the National Human Genome Research Institute (NHGRI), after some 15 years of leadership. While announcing his plans, Collins said that he is proud of his accomplishments and those of his colleagues—most notably, the mapping of the human genome [see "Deciphering the Code of Life"; SciAm, December 1999]. On leaving his post, the 58-year-old geneticist stated that he wanted the freedom to write books and explore opportunities that are off-limits to federal employees. The signing into law of the Genetic Information Nondiscrimination Act in May also contributed to his decision, he said, because it provided the assurance he needed that his research would move forward even without him at the helm. Alan E. Guttmacher, deputy director of NHGRI for the past six years, will serve as acting director.

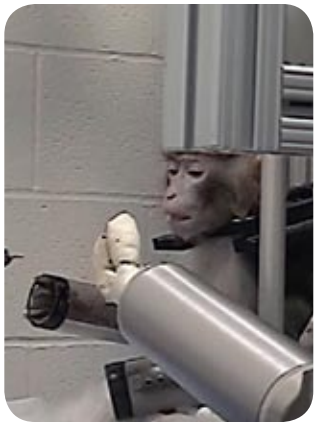
—*Larry Greenemeier*

MISSION ACCOMPLISHED: Francis S. Collins, who led the Human Genome Project, steps down.

Monkey Think, Monkey Do

Neuroprosthetics took another step forward when University of Pittsburgh researchers got two rhesus macaques to feed themselves using mentally controlled robotic arms. The scientists connected a grid of 100 electrodes to neurons in the monkeys' primary motor cortex. The grid picked up the neural activity and relayed it to a computer that controlled a nearby prosthetic arm. The monkeys succeeded in grabbing and eating fruit dangled in front of them 61 percent of the time, which, though lower than hoped, compares favorably to similar efforts in which monkeys (and humans) have moved objects in virtual environments [see "Controlling Robots with the Mind"; SciAm, October 2002]. Many challenges remain, however, before people can ever be fitted with mind-controlled limbs—the electrodes, for instance, must be made more durable and the gripping force of the prosthetics more variable. Grab onto these results in the May 29 *Nature*.

—*Nikhil Swaminathan*



FEED ME! A monkey controls a robot arm with its mind to eat.

Smart Sewer Control

Inexpensive, thumb-size computers that incorporate sensors and radio transceivers could link up to create ad hoc wireless networks useful for monitoring wildlife behavior, factory work and other spread-out activities [see "Smart Sensors to Network the World"; SciAm, June 2004]. In an effort to control storm runoff in South Bend, Ind., engineers from Purdue University, the University of Notre Dame and a local start-up firm called EmNet will create what they believe will be the largest such network in a permanent, industrial setting. They plan to attach 105 smart sensors to the undersides of manhole covers and to install smart valves in sewers to prevent backflow automatically. The network, to be completed in 2009, should also work in other cities where sewage and storm runoff share drainage systems.

A Glimpse of the Past

Several dozen indigenous tribes that have never been contacted by the modern world live in Amazonia. The existence of one group was photographed near the border of Brazil and Peru, from a low-flying airplane sent by FUNAI, Brazil's National Foundation for Indigenous Peoples. The flights, between April 28 and May 2, produced several astonishing images of the tribe, which FUNAI did not identify; in one shot, the men, wearing red body paint, can be seen pointing arrows at the aircraft. Brazil's anthropological philosophy is to leave these tribes alone and keep their positions secret to prevent cultural contamination and dislocation by development [see "Prime Directive for the Last Americans"; SciAm, May 2007].

PAUL FRANZ *AP Photo* (*Collins*); MOTORLAB, UNIVERSITY OF PITTSBURGH SCHOOL OF MEDICINE (*monkey prosthetics*); REUTERS/HO NEW (*indigenous people*)

IN THIS ISSUE: Lying in the MRI ■ Asthma ■ Too-Quiet Hybrids ■ Mars ■ Wildfires and Carbon ■ Cancer Cost ■ Cheaper Solar

NEUROSCIENCE

Lighting Up the Lies

Will brain scans ever be able to tell if you're really being deceptive? BY GARY STIX

Last year Sean A. Spence, a professor at the school of medicine at the University of Sheffield in England, performed brain scans that showed that a woman convicted of poisoning a child in her care appeared to be telling the truth when she denied committing the crime. This deception study, along with two others performed by the Sheffield group, was funded by Quickfire Media, a television production company working for the U.K.'s Channel 4, which broadcast videos of the researchers at work as part of a three-part series called "Lie Lab." The brain study of the woman later appeared in the journal *European Psychiatry*.

Functional magnetic resonance imaging (fMRI) purports to detect mendacity by seeing inside the brain instead of tracking peripheral measures of anxiety—such as changes in pulse, blood pressure or respiration—measured by a polygraph. Besides drawing hundreds of thousands of viewers, fMRI has pulled in entrepreneurs. Two companies—Cephos in Pepperell, Mass., and No Lie MRI in Tarzana, Calif.—claim to predict with 90 percent or greater certitude whether you are telling the truth. No Lie MRI, whose name evokes the casual familiarity of a walk-in dental clinic in a strip mall, suggests that the technique may even be used for "risk reduction in dating."

Many neuroscientists and legal scholars doubt such claims—and some even question whether brain scans for lie detection will ever be ready for anything but more research on the nature of deception and the brain.

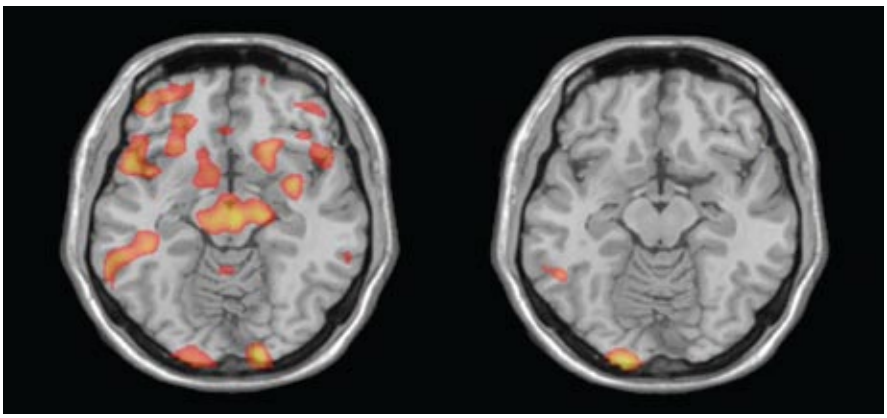
An fMRI machine tracks blood flow to activated brain areas. The assumption in lie detection is that the brain must exert extra effort when telling a lie and that the regions that do more work get more blood. Such areas light up in scans; during the lie studies, the illuminated regions are primarily involved in decision making.

To assess how fMRI and other neuroscience findings affect the law, the MacArthur Foundation put up $10 million last year to pilot for three years the Law and Neuroscience Project. Part of the funding will attempt to set criteria for accurate and reliable lie detection using fMRI and other brain-scanning technology. "I think it's not possible, given the current technology, to trust the results," says Marcus Raichle, a neuroscientist at the Washington University School of Medicine in St. Louis who heads the project's study group on lie detection. "But it's not impossible to set up a research program to determine whether that's possible."

A major review article last year in the *American Journal of Law and Medicine* by Henry T. Greely of Stanford University and Judy Illes, now at the University of British Columbia, explores the deficiencies of existing research and what may be needed to move the technology forward. The two scholars found that lie detection studies conducted so far (still less than 20 in all) failed to prove that fMRI is "effective as a lie detector in the real world at *any* accuracy level."

Most studies examined groups, not individuals. Others have not been replicated. Subjects in these studies were healthy young adults—making it unclear how the results would apply to someone who takes a drug that affects blood pressure or has a blockage in an artery. And the two researchers questioned the specificity of the lit-up areas; they noted that the regions also correlate with a wide range of cognitive behaviors, including memory, self-monitoring and conscious self-awareness.

The biggest challenge—and one for which the Law and Neuroscience Project is already funding new research—is how to diminish the artificiality of the test pro-



DID YOU STEAL THE WATCH? **The question, posed to a woman who pretended to lift a timepiece, illuminated an MRI image (*left*), in contrast to a question about stealing a ring (*right*).**

ANDREW KOZEL AND MARK GEORGE *Medical University of South Carolina* AND STEVE LAKEN *Cephos Corporation*

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tocol. Lying about whether a playing card is the seven of spades may not activate the same areas of the cortex as answering a question about whether you robbed the corner store. In fact, the most realistic studies to date may have come from the Lie Lab television programs.

The two companies marketing the technology are not waiting for more data. Cephos is offering scans without charge to people who claim they were falsely accused if they meet certain criteria in an effort to get scans accepted by the courts. Allowing scans as legal evidence could open a potentially huge and lucrative market. "We may have to take many shots on goal before we actually see a courtroom," says Cephos chief executive Steven Laken. He asserts that the technology has achieved 97 percent accuracy and that the more than 100 people scanned using the Cephos protocol have provided data that have resolved many of the issues that Greely and Illes cited.

But until formal clinical trials prove that the machines meet safety and effectiveness criteria, Greely and Illes have called for a ban on nonresearch uses. Trials envisaged for regulatory approval hint at the technical challenges. Actors, professional poker players and sociopaths would be compared against average Joes. The devout would go in the scanner after nonbelievers. Testing would take into account social setting. White lies—"no, dinner really was fantastic"—would have to be compared against untruths about sexual peccadilloes to ensure that the brain reacts identically.

The potential for abuse prompts caution. "The danger is that people's lives can be changed in bad ways because of mistakes in the technology," Greely says. "The danger for the science is that it gets a black eye because of this very high profile use of neuroimaging that goes wrong." Considering the long and controversial history of the polygraph, gradualism may be the wisest course to follow for a new diagnostic that probes an essential quality governing social interaction.

HEALTH POLICY

Change in the Air

Banning CFC-driven inhalers could levy a toll on asthma sufferers BY EMILY HARRISON

A federal ban on ozone-depleting chlorofluorocarbons (CFCs), to conform with the Clean Air Act, is, ironically, affecting 22.9 million people in the U.S. who suffer from asthma. Generic inhaled albuterol, which is the most commonly prescribed short-acting asthma medication and requires CFCs to propel it into the lungs, will no longer be legally sold after December 31, 2008. Physicians and patients are questioning the wisdom of the ban, which will have an insignificant effect on ozone but a measurable impact on wallets: the reformulated brand-name alternatives can be three times as expensive, raising the cost to about $40 per inhaler. The issue is even more disconcerting considering that asthma disproportionately affects the poor and that, according to recent surveys, an estimated 20 percent of asthma patients are uninsured.

"The decision to make the change was political, not medical or scientific," says pharmacist Leslie Hendeles of the University of Florida, who co-authored a 2007 paper in the *New England Journal of Medicine* explaining the withdrawal and transition. In 1987 Congress signed on to the Montreal Protocol on Substances That Deplete the Ozone Layer, an international treaty requiring the phasing out of all nonessential uses of CFCs. At that time, medical inhalers were considered an essential use because no viable alternative propellant existed. In 1989 pharmaceutical companies banded together and eventually, in 1996, reformulated albuterol with hydrofluoroalkane (HFA), an ozone-safe propellant. After more than one brand of HFA-albuterol became available, the U.S. Food and Drug Administration declared in 2005 that CFC inhalers were no longer essential and must be completely off the shelves by the last day of this year.

PRICE SHOCK: Albuterol inhalers that contain no ozone-damaging CFCs (*left*) cost three times more than generic inhalers that use CFCs (*right*), which are to be phased out completely by December 31.

EMILY HARRISON

The transition began quietly, but as more patients see their prescriptions change and costs go up, many question why this ban must begin before generics become available. At least one member of the FDA advisory committee, Nicholas J. Gross of the Stritch-Loyola School of Medicine, has publicly regretted the decision, recanting his support and requesting that the ban be pushed back until 2010, when the first patent expires.

Gross notes that the decision had nothing to do with the environment. Albuterol inhalers contributed less than 0.1 percent of the CFCs released when the treaty was signed. "It's a symbolic issue," Gross remarks.

Some skeptics instead point to the billions of dollars to be gained by the three companies holding the patents on the available HFA-albuterol inhalers, namely GlaxoSmithKline, Schering-Plough and Teva. Although the FDA advisory committee recognized that the ex-

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penses would go up, Hendeles says, it also believed that the companies would help defray the added costs for individuals. Firms, for instance, had committed to donating a million HFA inhalers to clinics around the country. According to Hendeles, GlaxoSmithKline did not follow through, although Schering-Plough and Teva did. GlaxoSmithKline did not respond to requests for comment.

The issue now, Hendeles says, is that pharmaceutical-grade CFCs are in short supply, and the public faces the risk of a shortage of albuterol inhalers if the FDA does not continue promoting the production of HFA inhalers. He posits that even costs of generics would go up as CFCs become scarcer. Gross disagrees, saying that the inhaler shortage and the closure of CFC manufacturing plants are a result of the ban.

The HFA inhalers also have encountered resistance because some asthmatics insist that they do not work as well as the CFC variety. But, Hendeles says, the differences are in the mechanics and maintenance—unlike CFC inhalers, the HFA versions must be primed more diligently and rinsed to accommodate the stickier HFA formulation. They also run out suddenly without the waning experienced with a CFC inhaler, which warns users that the device is running low. "Pharmacists may not tell people of these things, and the doctors don't know," Hendeles says.

The main public health issue in this decision may be the side effects of the economics, not the drug chemistry. Multiple studies have shown that raising costs leads to poorer adherence to treatment. One study discovered that patients took 30 percent less antiasthma medication when their co-pay doubled. In the case of a chronic disease such as asthma, it is particularly difficult to get people to follow regular treatment plans. "Generally speaking, for any reason you don't take medication, cost makes it more likely" that you do not, comments Michael Chernew, a health policy expert at Harvard Medical School.

Such choices to forgo medication could affect more than just the patients themselves. "For example," Hendeles points out, "in a pregnant mother with untreated asthma, less oxygen is delivered to the fetus, which can lead to congenital problems and premature birth." And considering that the disease disproportionately strikes the poor, what seemed to be a good, responsible environmental decision might in the end exact an unexpected human toll.

FIELD NOTES

Didn't Hear It Coming

Must hybrid cars be louder to be safe for pedestrians? BY SARAH SIMPSON

RIVERSIDE, CALIF.—People love their hybrid automobiles because, above all, they sip rather than guzzle now pricey gasoline. But as the owner of a standard minivan, I also covet a less touted benefit of electric engines: they are delightfully quiet.

So when I heard a graduate student say his group's latest research suggests that hybrid gas-electric vehicles are *too* quiet, my ears perked up. He described his colleagues' vision to equip these cars with sound-emitting devices to warn pedestrians. Were they planning to load a Toyota Prius with annoying beeps or the roar of a Maserati?

Certainly there seems to be some justification. In experiments led by perceptual psychologist Lawrence D. Rosenblum of the University of California, Riverside, blindfolded subjects who listened to recordings of cars approaching at five miles per hour could locate the familiar hum of a Honda Accord's internal-combustion engine 36 feet away. But they failed to identify a Prius, running in electric mode, until it came within 11 feet—affording them less than two seconds to react before the vehicle reached their position. And that was in the absence of traffic noise or other distractions.

SOUNDS FOR SAFETY: **Pedestrians are used to engine noise alerting them to the presence of moving vehicles. The sound cue disappears for a hybrid car in its electric mode.**

SUPERSTUDIO/GETTY IMAGES

In a second trial, Rosenblum added some realistic background noise to the recordings. My own appreciation of the safety issue stepped up dramatically when I experienced this scenario for myself: the Prius glided past me, undetected, time and again. By the rules of the game, I was hybrid roadkill 40 times over—as were the majority of Rosenblum's formal subjects. In con-

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trast, I correctly determined the approach direction of the Accord in all 40 attempts, from an average of 22 feet away.

Whether these laboratory results translate into the real world is unclear, from a scientific point of view. No concrete evidence proves that hybrid cars are involved in more pedestrian accidents than their noisier counterparts. And recent studies from Western Michigan University indicate that hybrids and conventional vehicles are equally safe when traveling more than about 20 miles per hour, because tire and wind noise generate most of the audible cues at those speeds. Hybrids also tested safe when leaving a stoplight; all Prius models in the study engaged their internal-combustion engines when accelerating from a standstill.

But many groups are not awaiting scientific certainty—or a death toll—to take action. Last November the Society of Automotive Engineers created a special committee to examine whether hybrid cars should be made more audible for the sake of pedestrians, particularly the blind. In April congressional lawmakers introduced a bill designed to tackle the same question, and the National Highway Traffic Safety Administration held a public hearing on the topic in June.

Adding noise to hybrids may be inevitable, but at least it won't have to be loud, Rosenblum says. That good news stems from the human brain's extreme sensitivity to approaching sounds relative to those that are fixed or moving away. Because they are more likely to pose a threat, approaching sounds most readily stimulate regions of the brain associated with motor action, he explains. Also, a large number of brain cells are specially attuned to sounds that get louder—which usually means they are drawing near.

So a warning can be subtle—as long as it's the right kind of sound. Chirps, beeps and alarms are more distracting than useful, say Rosenblum and Everett Meyer of Enhanced Vehicle Acoustics in Santa Clara, Calif.; the best sounds for alerting pedestrians would be carlike—akin to the soft purr of an engine or the slow roll of tires across pavement.

Even with sound-emitting safety measures in the works, Robert S. Wall Emerson of Western Michigan University predicts a future of more tranquil transportation. Several high-end (and not so high end) gas-powered motor vehicles are already quieter than hybrids, he says. Ironically, in Wall Emerson's most recent studies, hybrid SUVs turned up *noisier* than many internal-combustion vehicles. Pedestrian safety, he points out, is not a hybrid issue. It's a quiet car issue.

Sounding Out Sounds

By summer's end, Enhanced Vehicle Acoustics in Santa Clara, Calif., hopes to introduce an aftermarket solution to break the hybrid silence: speakers mounted behind the tires that project an audible warning toward pedestrians. Although the sound is still being tested, its inventors say it is *not* a chirp, beep or whistle; it is quieter than a combustion engine, changes frequency as the car speeds up or slows down, and shuts off when the car accelerates beyond about 20 miles per hour. They say dealerships will charge $395 for parts and installation, which will take about 30 minutes.

PLANETARY SCIENCE

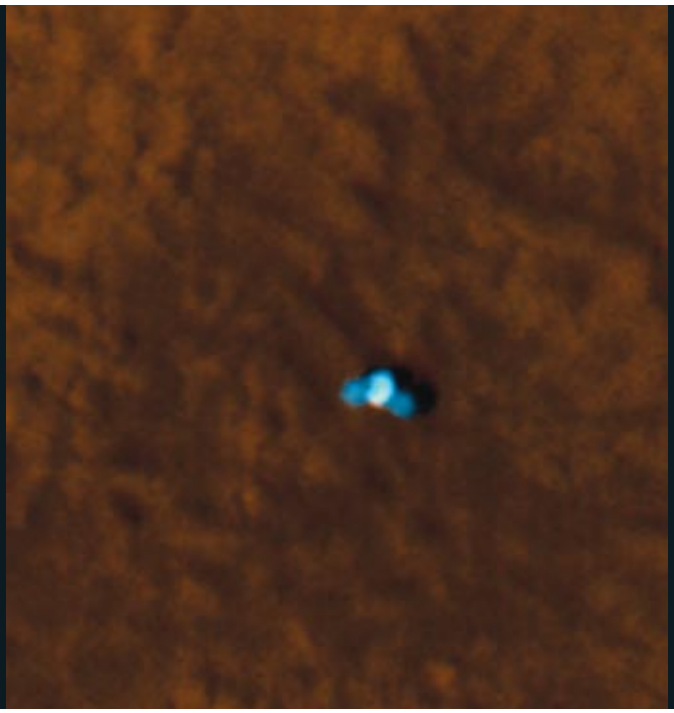
Seeing Red

New close-ups of Mars, courtesy of Phoenix

BY PHILIP YAM

Following in the pad prints and rover tracks of Viking 1 and 2, Mars Pathfinder, Spirit and Opportunity, the Mars Phoenix lander became Earth's sixth successful visitor to the surface of the Red Planet. Using a maneuver involving parachutes and rocket thrusters, the craft touched down on May 25, to the delight of NASA mission controllers and space fans everywhere. The Mars Reconnaissance Orbiter, one of three craft currently circling Mars, spotted the lander, with its two solar panels splayed out (*right*).

One of the first photographs returned by Phoenix, a shot of the northern plains of Mars, shows pebbles and



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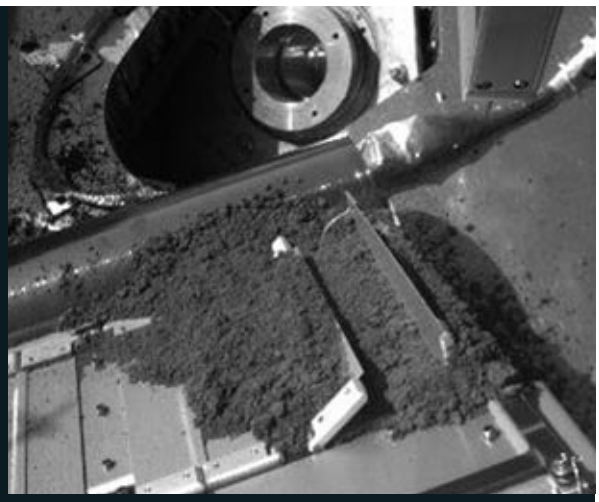

polygonal patterns (*left*), which probably result from the seasonal expansion and contraction of ice near the surface. Curiously, the polygons, about 1.5 to 2.5 meters in diameter, were much smaller than estimates made from earlier orbital images, suggesting that the area may be more complex and dynamic than previously thought.

With its 2.4-meter-long robotic arm, Phoenix scooped up some Martian dirt on June 6, but the first attempt to deliver the sample to onboard equipment for analysis—the hope is to find water—stalled when the Martian soil proved to be clumpier than anticipated. The sample sat on top of metal screens meant to sift out smaller particles (*above*). Mission controllers had to come up with a means to bypass the problem, including instructing Phoenix to turn on a mechanical screen shaker in an effort to dislodge the material. The seventh and final round of shaking did the trick.

Phoenix should last to September but probably not much beyond that. For most of 2009, it will be encased in dry ice, as the Martian winter arrives and carbon dioxide condenses out of the atmosphere, covering the region.

For the latest coverage, see **www.SciAm.com/aug2008**

NASA/JPL-CALTECH/UNIVERSITY OF ARIZONA (*left*);
NASA/JPL-CALTECH/UNIVERSITY OF ARIZONA/MAX PLANCK INSTITUTE (*right*)

ENVIRONMENT

The Puzzling Inferno

When saving trees means less carbon storage BY KEREN BLANKFELD SCHULTZ

Wildfires wreaked havoc across southern California last year, resulting in billions of dollars in irreparable damage. Not surprisingly, land managers and agencies this season have mobilized fire crews and equipment to stop the flames before they spread. In the meantime, however, researchers studying the amount of carbon that forests and vegetation harbor have stumbled on a finding that presents an added quandary to fire management: suppressing fires means that less carbon is stored in trees.

The team, led by Michael L. Goulden of the University of California, Irvine, compared the biomass of California's wild forests in the 1930s with those in the 1990s using data compiled by two forest census takers: the Wieslander Vegetation Type Mapping Project at the University of California, Berkeley, and the U.S. Forest Service's Forest Inventory and Analysis program. In evaluating the two sets of data, the scientists found that the density in midaltitude conifer forests increased by 34 percent during the 60 years that elapsed. Yet contrary to conventional wisdom—that more trees mean additional carbon storage—they found that the amount of carbon held actually decreased by 26 percent in the same period.

"This is a nice example of a counterintuitive result," remarks Richard Houghton of the Woods Hole Research Center,

Going to Blazes

Last year in the U.S., 85,705 wildfires burned 9,328,045 acres, according to the National Interagency Coordination Center. California suffered some 9,000 fires, more than any other state. This year's wildfire outlook continues the recent trend of increased risk. The National Interagency Fire Center Predictive Services has forecast "above normal significant fire" potential in the deserts of southern California through September. Although the number of wildfires has decreased during the past 200 years, the severity has risen as human populations encroach on natural ecosystems, according to the U.S. Geological Survey.

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who was not a part of the study but had come up with the idea for it when researching large carbon sinks in North America.

The logic behind the unanticipated finding comes down to the size of the trees that are being saved by fire suppression, says Goulden, whose study is being published this summer by *Geophysical Research Letters*. Over the past few decades firefighters have stopped the ground blazes common in California that would have otherwise likely wiped out the smaller trees and undergrowth. Instead these forests now have many small and midsize trees, adding to the forest's density.

In turn, Goulden adds, when forests in the western U.S. inevitably go through periods of extreme drought, the entire forest is put under severe stress. The larger trees, which require more water and oxygen to survive and experience higher exposure to the drying sun and wind, tend to be the casualties of the drought. Trees measuring 90 centimeters or more in height might contain as much carbon as 50 to 75 small trees that measure between 10 and 30 centimeters in height.

"In terms of trying to nail down the United States net carbon budget," Houghton says, "we should be more careful of counting forest thickening as a sink."

Preserving the heftier trees is the easy solution to augmenting carbon storage and allowing them to play their ecological roles—they offer varied habitats and shape the land—but the responsibility of fire management remains complex. Nathan L. Stephenson, a research ecologist at the U.S. Geological Survey's Western Ecological Research Center, is not so sure that Goulden's findings will change much of the current efforts in fire management.

As the climate changes and puts stress on plant life, Stephenson says, it is probably better for the forest to get back to the way it used to look: thinner and less crowded. In fact, the national parks of the Sierra Nevada Mountains, with which he closely works, already use prescribed fire to thin forests. Burning or cutting down trees will release some carbon into the atmosphere. But at least, Stephenson notes, "you reduce the chance that you're going to lose all [the carbon] in a catastrophic wildfire."

STEVEN K. DOL *Zuma/Corbis*

FIRE AWAY: Wildfires, such as this one that raged near Cerritos, Calif., in 2004, may in the long run actually improve a forest's ability to sequester carbon.

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MEDICAL ECONOMICS

Bills of Health

In discussing treatments, cancer doctors plan to include cost BY JESSICA WAPNER

Oncologists will soon be adding "financial counselor" to their job description. With an increasing number of cancer patients suffering economic hardships as a side effect of expensive therapy, most oncologists are finding that cost needs to be considered as part of treatment options. Leading cancer organizations are now working on incorporating cost into treatment guidelines and other materials. The change, which departs from the current American medical ethos, is fraught with thorny questions not only for cancer doctors and patients but also for the health care system at large.

The U.S. spends about $200 billion annually on cancer care; many new drugs cost several thousand dollars monthly. For patients, co-payments represent the most severe sappers of bank accounts. Increasingly, insurers are holding patients accountable for up to 20 percent of the prescription price. Covered drugs being used off-label (for an indication not formally approved but still medically appropriate) can carry co-pays of up to 30 percent.

COST may be considered in cancer treatment.

"Patients are having to make financial sacrifices related to treatment choice," says Neal L. Meropol, an oncologist at Fox Chase Cancer Center in Philadelphia. High out-of-pocket costs have led many patients to forgo particular therapies. One study found that treatment-related expenses consumed 27 percent of the annual income among low-income cancer patients.

The concern also pertains to the societal impact of pricey treatments. Considering that many patients are Medicare beneficiaries, expensive drugs are devouring federal health care dollars, often for only minimal survival gains. As Meropol describes, the U.S. has shunned the rationing of health care embraced in many other countries: "That's in part a cultural bias that no price is too high for an improvement in health."

The integration of cost into cancer treatment guidelines could be signifying a broader shift in health care. "I do think we're moving to a point where our society will start to be more comfortable with considering cost in decisions about what treatments we will pay for," Meropol remarks. Some experts even posit that the no-holds-barred attitude drives up cost and that reining it in might lower drug prices to points that reflect what the market will bear.

Forthcoming guidelines from the two main U.S. cancer societies will offer the safe harbor of a standard approach for oncologists to follow when discussing cost. One is the American Society of Clinical Oncology (ASCO). Meropol, who is part of an ASCO task force studying the cost of cancer care, says that one first step is creating a database of co-pays for all cancer drugs charged by various insurance providers. The group is also focusing on research, physician education and patient support. As he sees it, "the task force's overall goal is to make recommendations and develop tools to assist oncologists in dealing with issues of cost as they relate to quality oncology care." Diane S. Blum, executive director of the patient-advocacy organization CancerCare, says that advocacy groups support these efforts. ASCO-issued cost guidance should come out this year.

The second set of guidelines is coming from the National Comprehensive Cancer Network (NCCN), a nonprofit alliance of 21 cancer centers. It has convened expert panels to compare drug regimens according to their effectiveness, toxicity and, for the first time, costs. The panels will weigh all these factors together in their recommendations for the best treatment options. Costs will also be added into the NCCN compendium of drugs and biologics. As with ASCO, the results of these efforts will start rolling out within the year.

But NCCN's chief executive William T. McGivney has misgivings about trying to resolve cost issues in the clinic. He agrees that NCCN should address the needs of its customers (oncologists), but he sees this response as an unjust solution. "I think the organizations that are making substantial amounts of money off the health care system—the private payers and the drug companies—they ought to be the ones fighting this issue out," McGivney says. Foisting the problem on patients, he points out, places an unfair burden on the constituency of the cancer care system that is the most taxed and the least equipped for complex, cost-versus-benefit analyses.

In addition, Meropol recognizes the "potential for conflict between an oncologist's perceived responsibility to society and perceived responsibility to individual patients." If those allegiances are at odds, patient care could be compromised.

Ultimately, the decision on which treatment to pursue will always rest with the patient. The undeniable reality for oncologists is that providing high-quality care now means discussing the price of it, too.

Jessica Wapner is based in New York City.

MASON MORFIT *The Medical File/Peter Arnold, Inc.*

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ENERGY

Sunny Days for Silicon

Baby steps for making solar as cheap as coal power BY STEVEN ASHLEY

The old saw that "the devil is in the details" characterizes the kind of needling obstacles that prevent an innovative concept from becoming a working technology. It also often describes the type of problems that must be overcome to shave cost from the resulting product so that people will buy it.

Emanuel Sachs of the Massachusetts Institute of Technology has struggled with many such little devils in his career-long endeavor to develop low-cost, high-efficiency solar cells. In his latest effort, Sachs has found incremental ways to boost the amount of electricity that common photovoltaics (PVs) generate from sunlight without increasing the costs. Specifically, he has raised the conversion efficiency of test cells made from multicrystalline silicon from the typical 15.5 percent to nearly 20 percent—on par with pricier single-crystal silicon cells. Such improvements could bring the cost of PV power down from the current $1.90 to $2.10 per watt to $1.65 per watt. With additional tweaks, Sachs anticipates creating within four years solar cells that can produce juice at a dollar per watt, a feat that would make electricity from the sun competitive with that from coal-burning power plants.

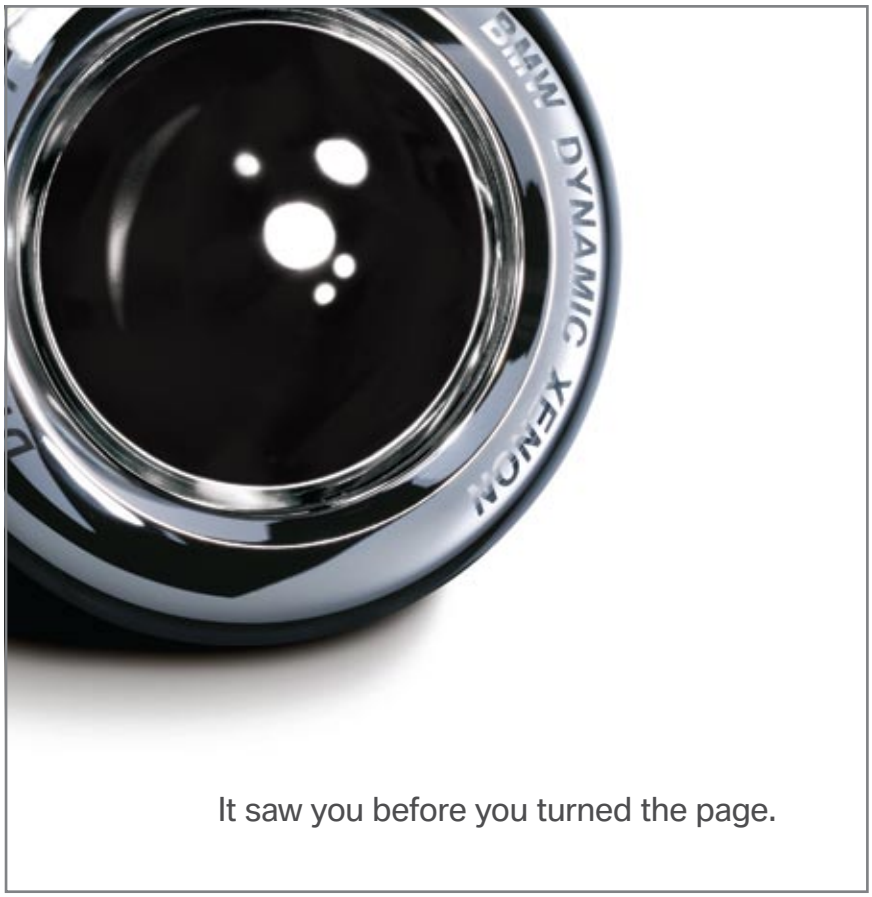
Most PV cells, such as those on home rooftops, rely on silicon to convert sunlight into electric current. Metal interconnects then funnel the electricity out from the silicon to power devices or to feed an electrical grid.

Since solar cells became practical and affordable three decades ago, engineers have mostly favored using single-crystal silicon as the active material, says Michael Rogol, managing director of Germany-based Photon Consulting. Wafers of the substance are typically sawed from an ingot consisting of one large crystal that has been pulled like taffy out of a vat of molten silicon. Especially at first, the high-purity ingots were left over from integrated-circuit manufacture, but later the process was used to make PV cells themselves, Rogol recounts. Although single-crystal cells offer high conversion efficiencies, they are expensive to make. The alternatives—multicrystalline silicon cells, which factories fabricate from lower-purity, cast ingots composed of many smaller crystals—are cheaper to make, but unfortunately they are less efficient than single-crystal cells.

Sachs, who has pioneered several novel ways to make silicon solar cells less costly and more effective, recently turned his focus to the details of multicrystalline sili-

Silicon Price Cuts

The cost of silicon solar cells is likely to fall as bulk silicon prices drop, according to the U.S. Energy Information Administration and the industry tracking firm Solarbuzz. A steep rise in solar panel sales in recent years had led to a global shortage of silicon because production capacity for the active material lagged behind, but now new silicon manufacturing plants are coming online. The reduced materials costs and resulting lower system prices will greatly boost demand for solar-electric technology, according to market watcher Michael Rogol of Photon Consulting.



It saw you before you turned the page.

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SUN POWER ON THE FARM: Use of solar photovoltaic panels, such as those on this barn, is set to become more widespread as clever design makes multicrystalline silicon cells—the most common type—more cost-competitive with conventional power sources.

VISUALS UNLIMITED/CORBIS

con cell manufacture. The first small improvement concerns "the little silver fingers that gather electric current from the surface of the bulk silicon," he explains. In conventional fabrication processes, cell manufacturers use screen-printing techniques ("like high-accuracy silk-screening of T-shirts," Sachs notes) and inks containing silver particles to create these bus wires. The trouble is that standard silver wires come out wide and short, about 120 by 10 microns, and include many nonconductive voids. As a result, they block considerable sunlight and do not carry as much current as they should.

At his start-up company—Lexington, Mass.–based 1366 Technologies (the number refers to the flux of sunlight that strikes the earth's outer atmosphere: 1,366 watts per square meter)—Sachs is employing "a proprietary wet process that can produce thinner and taller" wires that are 20 by 20 microns. The slimmer bus wires use less costly silver and can be placed closer together so they can draw more current from the neighboring active material, through which free electrons can travel only so far. At the same time, the wires block less incoming light than their standard counterparts.

The second innovation alters the wide, flat interconnect wires that collect current from the silver bus wires and electrically link adjacent cells. Interconnect wires at the top can shade as much as 5 percent of the area of a cell. "We place textured mirror surfaces on the faces of these rolled wires. These little mirrors reflect incoming light at a lower angle—around 30 degrees—so that when the reflected rays hit the glass layer at the top, they stay within the silicon wafer by way of total internal reflection," Sachs explains. (Divers and snorkelers commonly see this optical effect when they view water surfaces from below.) The longer that light remains inside, the more chance it has to be absorbed and transformed into electricity.

Sachs expects that new antireflection coatings will further raise multicrystalline cell efficiencies. One of his firm's future goals will be a switch from expensive silver bus wires to cheaper copper ones. And he has a few ideas regarding how to successfully make the substitution. "Unlike silver, copper poisons the performance of silicon PVs," Sachs says, "so it will be crucial to include a low-cost diffusion barrier that stops direct contact between copper and the silicon." In this business, it's always the little devilish details that count.

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Data Points
Hurricane Hubbub

The number of major Atlantic storms has increased over the past 100 years, in concert with the rise in ocean temperatures. Contradicting some past conclusions, a study in *Nature Geoscience* predicts that as the world heats up, the number of hurricanes will decrease, although the storms will produce more rain. Rather than being driven by warmer waters per se, the 20th-century rise may have stemmed from temperature *differences* between the tropical Atlantic and other basins, which have not warmed as quickly. As sea-surface temperatures of the other basins catch up, storm frequency may decline.

Average number of hurricanes from:

1905 to 1930:	3.48
1931 to 1994:	5.08
1995 to 2005:	8.44

Rise in tropical Atlantic sea-surface temperature since 1900:
0.7 degree Celsius

Projected rise by 2100:
1.7 degrees C

PROJECTED DROP BY 2100 IN:
Tropical storms:
27 percent

Hurricanes, Category 1 and 2:
18 percent

Hurricanes, Category 3, 4 and 5:
8 percent

SOURCES: Nature Geoscience, *June 2008; National Oceanic and Atmospheric Administration;* Philosophical Transactions of the Royal Society A, *November 15, 2007 (historical data)*

BIOLOGY
Reconstructing the Very First Cell

Unlike modern cells, with their mitochondria, pores, nuclei and such, the very first cell, which emerged some 3.5 billion years ago, was simple. It probably consisted of just a membrane with genetic information inside—raising the question of how it could take in nutrients and reproduce. Harvard Medical School researchers have built a model of what the first cell may have looked like. Using fatty acids that likely existed on a primeval Earth, they created a membrane porous enough to let in nutrients but strong enough to protect the genetic material inside. In a test tube of water, the fatty acids formed into a ring around a strip of DNA. The investigators also added nucleotides—units of genetic material—which entered the cell, latched onto the DNA and replicated it over 24 hours. Scientists now must figure out how the original and copycat DNA strands can separate, which would enable the cell to divide and reproduce. The study turned up in the June 12 *Nature*. —*Nikhil Swaminathan*

REPELLENTS
DEET Beaters

New mosquito repellents work more than three times as long as DEET, currently the most widely used such chemical and the gold standard by which to judge alternatives. Researchers discovered them using an artificial neural network, which they first trained by supplying it with the molecular structures of 150 known repellents. The neural network then scanned a library of roughly 2,000 untested piperidines, compounds related to the active ingredient in black pepper that can ward off insects. Human volunteers then wore arm patches impregnated with the best candidates and held their arms motionless in cages filled with roughly 500 mosquitoes for one minute each day. While DEET repelled mosquito attacks for an average of 17.5 days, some of the new compounds lasted for up to 73 days, scientists at the University of Florida and the U.S. Department of Agriculture found. Buzz about the findings in the May 27 *Proceedings of the National Academy of Sciences USA*.
—*Charles Q. Choi*

BLOOD THIRST: Guess which hand got the DEET treatment? New DEET-free insect repellents can last three times longer.

MATERIALS
Iron-Tough Paper

Paper may not become obsolete after all—a new type can resist tearing better than cast iron. Materials made from cellulose fibers can be very strong, but they can also be brittle, ripping apart fairly easily when pulled. Now investigators at the Royal Institute of Technology in Stockholm and their colleagues have devised "nanopaper" that is remarkably tough. To make these sheets, the researchers treated wood pulp with enzymes and then pulverized it. Paper is typically made from fibers tens of microns in diameter, but the nanopaper swirls cellulose fibers together into tangles that are 10 to 40 nanometers wide. Its high tensile strength is likely explained by its weblike structure and the way the fibers adhere to one another. The recipe for the paper, which could find use as a construction material, was printed up in the June 9 issue of *Biomacromolecules*.
—*Charles Q. Choi*

GREGORY ALLEN *USDA, ARS Mosquito and Fly Research Unit, Gainesville, Fla. (bug repellent);* ILLUSTRATION BY MATT COLLINS

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In Brief

MICROBIAL COMPUTING

Scientists have made a DNA computer that puts bacteria to work solving a sorting problem (namely, one that involves flipping pancakes golden side up). The researchers modeled a simple two-pancake-flip problem using two DNA segments—one large and one short—and inserted them into the bacteria in random order and orientation. With the help of an enzyme, the segments would have a certain amount of time to flip to the correct position. Bacteria with the right answer were conveniently immune to antibiotics, which were used to wipe out those with incorrect answers. Because cells can reproduce, the number of microbial processors can increase exponentially to solve problems fast. *—Nikhil Swaminathan*

CATCH AN EXPLODING STAR

Scientists have pinpointed a star that flared in the ultraviolet (UV) portion of the spectrum for several hours before it blew apart. The finding represents the earliest visible sign of an imminent supernova. The UV rays result from a surge in temperature as an expanding internal shock wave strains to break free of the star; hence, they provide the last chance to collect data about the intact star before its destruction. The discovery comes shortly after researchers witnessed for the first time the x-rays that are released when the shock wave actually shreds the star. *—JR Minkel*

ARTIFICIAL CORNEAS IN SIGHT

Damage to the cornea—the eye's clear, outermost part—is the second leading cause of blindness, affecting 10 million people worldwide, but cornea transplants are often unavailable because of donor shortages or cultural barriers. Now Stanford University researchers find that artificial corneas made from advanced materials could soon eliminate the need for donations altogether. Similar to soft contact lenses, the newest artificial corneas consist of water-swollen hydrogels that mimic the abilities of real corneas, such as allowing the diffusion of nutrients. Get a clear view from the June 6 *Biotechnology Progress*. *—Charles Q. Choi*

NEUROPSYCHOLOGY

Is That Your Final Offer?

Serotonin, a chemical that in the brain affects mood, also seems to control behavioral reactions to unfairness. Researchers at the University of Cambridge depleted the serotonin levels of volunteers in part by feeding them a cocktail of amino acids that lacked tryptophan, an ingredient that the body needs to make serotonin. The volunteers then played an ultimatum game, in which they had to decide whether to accept an offer by a "proposer" to split, however unevenly, a pot of money. Rejection of the offer meant that no one got anything. Lack of serotonin, the experimenters found, made refusal more likely—for instance, 82 percent of serotonin-deprived individuals refused a 20 percent piece of the pie, compared with 67 percent of normal subjects given the same ultimatum. Take it or leave it from the study published online June 5 by *Science*.

—Philip Yam

EVOLUTION

Monogamy and the Queen Bee

For decades, a divisive debate has raged among biologists over the evolution of eusocial insects—those that thrive in cooperative societies of queens, workers and drones. On one side is the argument for "kin selection," a theory asserting that the nonreproducing members pass on their genes by helping relatives reproduce. The members of a colony should therefore be closely related. Yet those on the other side—most notably, renowned biologist Edward O. Wilson of Harvard University—contend that eusocial insects work together in colonies because it is to their individual advantage; their cooperative spirit is simply a consequence. If there is high relatedness in a colony, then it is a result of individuals choosing to stick around to reap the benefits of group life.

MONOGAMY kicked off the evolution of bees and other eusocial insects.

Researchers led by William Hughes of the University of Leeds in England say they have the first clear evidence that supports kin selection, rather than group selection, in eusociality. They examined 267 eusocial species of bees, wasps and ants and found that the insects evolved from monogamous conditions, which maximize a group's degree of relatedness. Moreover, they found that polyandry (having more than two mates) transpired only among lineages where workers had become permanently sterile—a prediction of kin selection theory for species that have become irrevocably eusocial. Behavioral biologist Andrew Bourke of the University of East Anglia in England says that the May 30 *Science* study indicates that kin selection is an essential precondition to eusociality.

Wilson, however, disagrees, asserting via e-mail that Hughes's work does not include data on many lineages that did not evolve eusociality and that the emergence of polyandry in eusocial societies has explanations not related to kin selection.

—Keren Blankfeld Schultz

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WILLIAM WHITEHURST *Corbis (eyeballs)*; HANS REINHARD *zefa/Corbis (honeycomb)*

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SciAm Perspectives

We Can Do More

The U.S. needs to expand support for agricultural science targeted at developing countries

BY THE EDITORS

Global food prices have roughly doubled in three years. At the World Food Summit in Rome in early June, United Nations secretary-general Ban Ki-moon recalled that on a trip to Liberia he encountered people who had once bought rice by the bag and whose cash now suffices for a meager cupful. The current crisis means that another 100 million hungry may join the 854 million who already lack sufficient daily nourishment.

An immediate response should include policies that discourage grain hoarding, that reapportion the way food aid is delivered and that ensure that subsidies for food purchases are carefully targeted to reach the truly poor. Just shipping more grain to Africa, by far the most vulnerable region, will not suffice. Over the long haul, science and technology have a big role to play. Finding nonfood substitutes for ethanol produced from corn or sugarcane would help. But the only lasting solution to hunger in Africa and elsewhere must focus on poor agricultural productivity.

U.S. secretary of agriculture Ed Schafer called on participants at the summit to consider the use of biotechnology to grow crops with higher yields that are capable of resisting assaults from inclement weather, disease or pests. Some activists, invoking fears about genetic manipulation of food crops, have jumped on the administration's stance as pandering to agribusiness and overhyping benefits from genetically modified organisms (GMOs).

That criticism is unfounded. Nongovernmental organizations that advocate exporting the organic food movement to Africa are at best misguided. Much of Africa practices what political scientist Robert Paarlberg calls "de facto organic farming," and overall productivity has plummeted. African small farmers achieve crop yields only one third of those obtained by farmers in developing countries in Asia. GMOs have the potential to increase productivity by incorporating beneficial traits that would, for one, allow crops to thrive even when rain is a rare event.

The Bush administration, never a beacon of enlightened social policymaking, would have come across more convincingly if it had incorporated biotechnology into a well-defined framework of research and development assistance. At the moment, genetically modifying cassava or cowpeas against viruses or insects is akin to producing hydrogen fuel cells in the energy arena. Both hold tremendous promise, and both are not ready for wide commercial dissemination.

The best hope for improving African crop yields today would be to borrow technology from the decades-old green revolution that transformed agriculture in Asia and Latin America. Using conventionally bred hybrid seeds, farmers in certain fertile areas of Ethiopia have witnessed their fields turn into a breadbasket that is rivaled in the sub-Saharan region of the continent only by South Africa. Eventually these same farmers will likely demand still better yields that will leave an opening for acceptance of genetically modified crops.

The Alliance for a Green Revolution in Africa (a partnership of the Rockefeller and Gates foundations) signed an agreement with three U.N. food agencies at the June summit meeting to bolster the lot of African small farmers. The Bush administration had asked in May that part of a recent aid package to address the food crisis go to agricultural development, including the planting of GMOs. More is needed, though. As the world's largest food aid donor, the U.S. channels most of its dollars to pay for acute emergencies, a response that, by law, requires shipping crops grown in Iowa or Kansas to needy countries—largely on U.S. ships. Meanwhile the U.S. Agency for International Development's funding for agricultural science in Africa dropped by 75 percent after inflation from the mid-1980s to 2004.

To avoid a crisis without end, we should back a program that not only delivers better seeds to African farmers but also devotes still more assistance to support improvements in soil, irrigation, roads and farmer education. Then, when necessary, we should use remaining aid money to buy either hybrid or genetically modified crops grown in African soil for local distribution. The U.S. farm lobby will howl in protest, but this action will be the best way to work toward putting African bread on African tables. ■

MATT COLLINS

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Sustainable Developments

Millennium Goals at the Midpoint

Overdue investments from rich nations could still transform Africa by 2015

BY JEFFREY D. SACHS

In September 2000 the world's leaders, assembled at the United Nations, adopted the Millennium Development Goals (MDGs) as shared commitments to fighting extreme poverty, hunger and disease through 2015. Halfway to the target date, there are heartening examples of dramatic progress, such as the 91 percent reduction in measles deaths in Africa and new inroads against malaria. Overall, the gains remain too slow, yet specific and accelerated investments in the poor countries can still deliver the MDGs on schedule.

Overcoming extreme poverty, hunger and disease requires not only the standard prescriptions for economic growth—rule of law, security, corruption held in check and open trade—but also targeted public investments in agriculture, health, education and infrastructure. They are needed to provide the basis for productive private-sector activity. For example, public investments in roads, power and port facilities could vividly increase the profitability of agricultural exports in sub-Saharan Africa. Such investments are complements to and preconditions for profitable private-sector investments, not replacements for them.

The MDG Africa Steering Group headed by U.N. secretary-general Ban Ki-moon recently led a critical review and identified a series of specific, high-priority public investments to be undertaken between now and 2015. For each investment area, practical strategies are available for immediate implementation (such as ways for controlling malaria and tuberculosis or for replenishing soil nutrients for smallholder farmers). Often powerful demonstration projects already exist and could be taken quickly to scale, as in the case of the Millennium Villages program that demonstrates the benefits of MDG investments in rural villages. What has been missing is neither the technology, the will, the plans, the methods of implementation, nor even the ways to control corruption in aid delivery but rather the needed financial help from the donor countries.

The basic problem, of course, is that the poor countries cannot afford the public investments on their own. The secretary-general's report identifies an additional $72 billion a year of donor financing needed to get the job done. This sum is sizable to be sure, though fully compatible with the donor countries' past pledges to Africa.

Here's the basic donor arithmetic: The combined income of the donor countries (Europe, the U.S., Canada and Japan) is now around $37 trillion a year; the required $72 billion only amounts to around 0.2 percent of the donors' gross national product. Donors have long promised to increase their aid from the current level of 0.28 percent of GNP ($104 billion) to 0.7 percent, so the additional 0.2 percent falls well within the aid levels already promised in pursuit of the MDGs.

Despite the major G8 countries' promise to double aid to Africa between 2004 and 2010, the aid from the donor nations has hardly increased. The U.S. actually had the lowest ratio of aid to GNP, at 0.16 percent in 2007; its aid to Africa was a mere 0.04 percent of GNP!

The failure of the donor countries to honor their commitment is now the limiting factor in achieving the MDGs in Africa. U.S. aid should be raised to around 0.5 percent of GNP by 2012 and then to 0.7 percent by 2015. That much aid would still be only a small fraction of the U.S. military budget (which is roughly 4.5 percent of GNP) and would help prevent far more expensive and far less effective military operations in impoverished and unstable regions.

The next president should signal to the world that the U.S. is actively supporting the MDGs by including them in the inaugural address next January. The global goodwill resulting from such a high-profile vow would be enormous. It would inspire the kind of confidence and hope that newly elected President John F. Kennedy did in 1961, when he famously committed the U.S. "for whatever period is required" to help the world's poor break the bonds of mass misery. ■

SCI AM An extended version of this essay is available at **www.SciAm.com/aug2008**

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Skeptic

Wheatgrass Juice and Folk Medicine

Why subjective anecdotes often trump objective data

BY MICHAEL SHERMER

The recent medical controversy over whether vaccinations cause autism reveals a habit of human cognition—thinking anecdotally comes naturally, whereas thinking scientifically does not.

On the one side are scientists who have been unable to find any causal link between the symptoms of autism and the vaccine preservative thimerosal, which in the body breaks down into ethylmercury, the culprit du jour for autism's cause. On the other side are parents who noticed that shortly after having their children vaccinated autistic symptoms began to appear. These anecdotal associations are so powerful that they cause people to ignore contrary evidence: ethylmercury is expelled from the body quickly (unlike its chemical cousin methylmercury) and therefore cannot accumulate in the brain long enough to cause damage. And in any case, autism continues to be diagnosed in children born after thimerosal was removed from most vaccines in 1999; today trace amounts exist in only a few.

The reason for this cognitive disconnect is that we have evolved brains that pay attention to anecdotes because false positives (believing there is a connection between A and B when there is not) are usually harmless, whereas false negatives (believing there is no connection between A and B when there is) may take you out of the gene pool. Our brains are belief engines that employ association learning to seek and find patterns. Superstition and belief in magic are millions of years old, whereas science, with its methods of controlling for intervening variables to circumvent false positives, is only a few hundred years old. So it is that any medical huckster promising that A will cure B has only to advertise a handful of successful anecdotes in the form of testimonials.

Take wheatgrass juice … if you can stomach it. The claims for its curative powers are bottomless. According to the Natural Medicines Comprehensive Database (the "bible" of natural medicines: www.naturaldatabase.com), wheatgrass is "used therapeutically for increasing hemoglobin production, improving blood sugar disorders such as diabetes, preventing tooth decay, improving wound healing, and preventing bacterial infections." And that's not all. "It is also used orally for common cold, cough and bronchitis, fever and colds, inflammation of mouth and pharynx, tendency to infection, gout, liver disorders, ulcerative colitis, cancer, rheumatic pain, and chronic skin problems."

The alleged salubrious effects of wheatgrass were promoted in the 1940s by a Lithuanian immigrant to Boston named Ann Wigmore, a holistic health practitioner who was inspired by the biblical story of King Nebuchadnezzar, recounted in Daniel 4:33, in which "he was driven from men, and did eat grass as oxen, and his body was wet with the dew of heaven, till his hairs were grown like eagles' feathers, and his nails like birds' claws." Wigmore also noted that dogs and cats eat grass when they are ill and feel better after regurgitation, which gave her the idea of the wheatgrass detox. Because we have fewer stomachs than cows do, she hatched the idea of blending freshly cut wheatgrass into juice form for easier digestion—through either orifice—a practice still employed today. She believed that the enzymes and chlorophyll in wheatgrass constitute its healing powers.

SHERMER, Sanford and Novella risk their taste buds to sample wheatgrass for the sake of science.

According to William T. Jarvis, a retired professor of public health at the Loma Linda University School of Medicine and founder of the National Council against Health Fraud (www.ncahf.org), this is all baloney: "Enzymes are complex protein molecules produced by living organisms exclusively for their own use in promoting chemical reactions. Orally ingested enzymes are digested in the stomach and have no enzymatic activity in the eater." Jarvis adds, "The fact that grass-eating animals are not spared from cancer, despite their large intake of fresh chlorophyll, seems to have been lost on Wigmore. In fact, chlorophyll cannot 'detoxify the body' because it is not absorbed."

I tried wheatgrass juice at the Oh Happy Days natural food store in Altadena, Calif., as part of an investigation for the pilot episode of *Skeptologists,* a series we hope to sell to a television network (where another biblical phrase is apropos: "Many are called, but few are chosen"). My co-stars—Kirsten Sanford, who has a Ph.D. in physiology and is now a science journalist, and Steven Novella, director of general neurology at the Yale School of Medicine—also imbibed. If a picture is worth a thousand words, I will double this essay's length by sharing the above snapshot. ■

Michael Shermer is publisher of Skeptic *(www.skeptic.com). His new book is* The Mind of the Market.

BRAD SWONETZ *(top)*; MATT FORE *New Rule Productions, 2008 (bottom)*

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Anti Gravity

Looking for a Sign

The most accurate horoscope a science magazine could ever hope to publish

BY STEVE MIRSKY

We Scientific Americans are emphatic empiricists. And although astronomy and astrology have common historical roots, the modern practice of astrology is total hooey. (And we say that only because we choose not to use stronger words than hooey in a family magazine.)

Nevertheless, some staffers were recently musing about what a horoscope would look like in our august pages. (Or September, even.) So here's a proof-of-concept. It's not based on science, because it's impossible to have a horoscope based on science. But it's science heavy. Specific predictions accompany individual zodiacal signs as per the form of the typical newspaper or magazine horoscope page (and shame on all you allegedly legitimate news outlets for running such garbage). Some of the predictions may seem intimately related to the sign in question. Even so, consider them all totally interchangeable, as the truly important aspect of the coordinates of your birth is the GDP at that time and place. And away we go.

Aquarius: "When you walk through a storm, hold your head up high" is a lovely song lyric but terrible advice if the storm is electrical.

Pisces: You fear the addition of fish proteins to ice cream, added to improve smoothness. But you're basically just a modestly modified fish—anatomically, physiologically and genetically. So take some omega-3 pills and read Neil Shubin's *Your Inner Fish,* just for the halibut.

Aries: Your attempt to clone your dog Binky based on the hope that Binky 2 will know where "original" Binky hid the leather wallet he took off your end table and hid for the last time just before he died of distemper betrays your utter ignorance of both cloning and Binky's deeply malevolent nature.

Taurus: While looking at a region of space in which a supernova was in progress, researchers at Princeton University recently noted the beginning of another supernova through the detection of x-rays. Which reminds me, the films came back, and the radiologist says your arm is broken in two places.

Gemini: The influence of genetics on behavior is apparently so strong that you and the identical twin brother you haven't seen since birth and don't even know about both spend most of your time watching sports on television, whereas the average American man only spends a great deal of his time watching sports on television.

Cancer: Rather than employing hemoglobin, the blood of the horseshoe crab contains hemocyanin, which binds oxygen with copper rather than iron. The crab's blood is therefore a beautiful pale blue rather than the bright red, viscous liquid that you will continue to lose unless you get a tourniquet on that busted arm.

Leo: "A fatal, Alzheimer's-like disease that attacks cheetahs' internal organs and has impeded breeding of the cats in captivity may be spread by their feces." Thus ran a report on May 12 at www.SciAm.com. So remember that when it comes to longevity, waste makes haste. What, you were expecting "cheetahs never prosper"?

Virgo: Some people are against the use of a cervical cancer vaccine because they fear it will promote promiscuity. This is roughly the equivalent of being against the use of the polio vaccine because it may increase the risk of drowning in public swimming pools. Anyway, get your shots already.

Libra: The good news is that you will be part of an investigation using the advanced forensic CSI techniques that you find so fascinating, methodologies like DNA amplification that can identify a person based on only the tiniest amounts of physical remains. That's also the bad news, if you see where we're going with this.

Scorpio: If you hadn't been born prematurely, you could have been a Sagittarius, maybe even a Capricorn. But it's the related fact that your mother smoked while she was pregnant that's the salient point in influencing your life's trajectory.

Sagittarius: You will go on a long journey when you become a highly trained astronaut and travel to the International Space Station to fix the toilet.

Capricorn: Your former opposition to embryonic stem cell research becomes grudging support when you realize that Michael J. Fox isn't shaking, you are. ■

PHOTOGRAPH BY FLYNN LARSEN; ILLUSTRATION BY MATT COLLINS

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Facing the Freshwater CRISIS

As demand for freshwater soars, planetary supplies are becoming unpredictable. Existing technologies could avert a global water crisis, but they must be implemented soon

By Peter Rogers

KEY CONCEPTS

- Global freshwater resources are threatened by rising demands from many quarters. Growing populations need ever more water for drinking, hygiene, sanitation, food production and industry. Climate change, meanwhile, is expected to contribute to droughts.
- Policymakers need to figure out how to supply water without degrading the natural ecosystems that provide it.
- Existing low-tech approaches can help prevent scarcity, as can ways to boost supplies, such as improved methods to desalinate water.
- But governments at all levels need to start setting policies and making investments in infrastructure for water conservation now. *—The Editors*

A friend of mine lives in a middle-class neighborhood of New Delhi, one of the richest cities in India. Although the area gets a fair amount of rain every year, he wakes in the morning to the blare of a megaphone announcing that freshwater will be available only for the next hour. He rushes to fill the bathtub and other receptacles to last the day. New Delhi's endemic shortfalls occur largely because water managers decided some years back to divert large amounts from upstream rivers and reservoirs to irrigate crops.

My son, who lives in arid Phoenix, arises to the low, schussing sounds of sprinklers watering verdant suburban lawns and golf courses. Although Phoenix sits amid the Sonoran Desert, he enjoys a virtually unlimited water supply. Politicians there have allowed irrigation water to be shifted away from farming operations to cities and suburbs, while permitting recycled wastewater to be employed for landscaping and other nonpotable applications.

As in New Delhi and Phoenix, policymakers worldwide wield great power over how water resources are managed. Wise use of such power will become increasingly important as the years go by because the world's demand for freshwater is currently overtaking its ready supply in many places, and this situation shows no sign of abating. That the problem is well-known makes it no less disturbing: today one out of six people, more than a billion, suffer inadequate access to safe freshwater. By 2025, according to data released by the United Nations, the freshwater resources of more than half the countries across the globe will undergo either stress—for example, when people increasingly demand more water than is available or safe for use—or outright shortages. By midcentury as much as three quarters of the earth's population could face scarcities of freshwater.

Scientists expect water scarcity to become more common in large part because the world's population is rising and many people are getting richer (thus expanding demand) and because global climate change is exacerbating aridity and reducing supply in many regions. What is more, many water sources are threatened by faulty waste disposal, releases of industrial pollutants, fertilizer runoff and coastal influxes of saltwater into aquifers as groundwater is depleted. Because lack of access to water can lead to starvation, disease, political instability and even armed conflict, failure to take action can have broad and grave consequences.

Fortunately, to a great extent, the technologies and policy tools required to conserve exist-

BIG SQUEEZE ON the world's freshwater resources looms as populations mushroom and incomes rise.

CARY WOLINSKY

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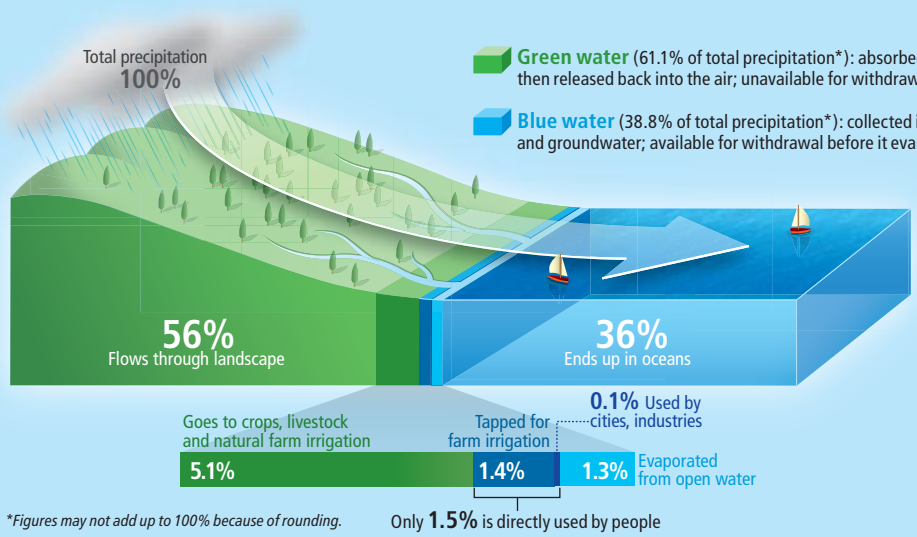
[THE CURRENT SITUATION]

Lots of Water, but Not Always Where It Is Needed

One hundred and ten thousand cubic kilometers of precipitation, nearly 10 times the volume of Lake Superior, falls from the sky onto the earth's land surface every year. This huge quantity would be enough to easily fulfill the requirements of everyone on the planet if the water arrived where and when people needed it. But much of it cannot be captured (*top*), and the rest is distributed unevenly (*bottom*).

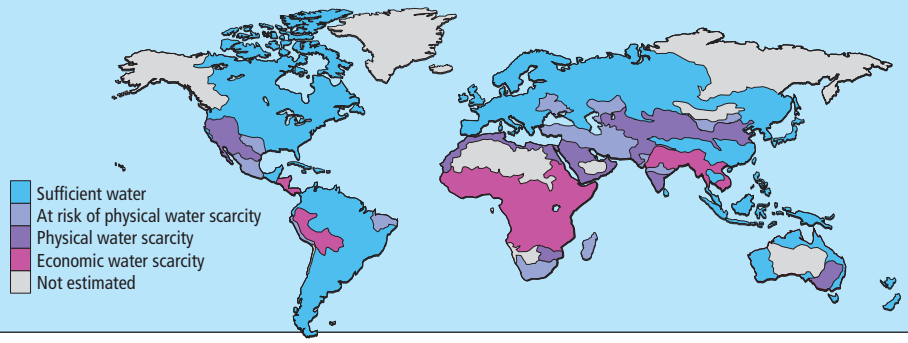


WHERE DOES THE RAIN GO?

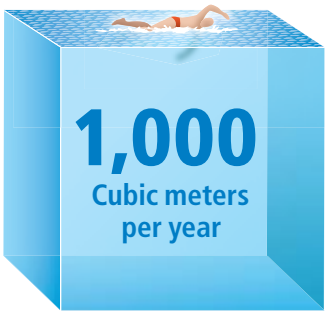
More than half of the precipitation that falls on land is never available for capture or storage because it evaporates from the ground or transpires from plants; this fraction is called green water. The remainder channels into so-called blue-water sources—rivers, lakes, wetlands and aquifers—that people can tap directly. Farm irrigation from these free-flowing bodies is the biggest single human use of freshwater. Cities and industries consume only tiny amounts of total freshwater resources, but the intense local demand they create often drains the surroundings of ready supplies.

WATER SUPPLIES TODAY

Much of the Americas and northern Eurasia enjoy abundant water supplies. But several regions are beset by greater or lesser degrees of "physical" scarcity—whereby demand exceeds local availability. Other areas, among them Central Africa, parts of the Indian subcontinent and Southeast Asia, contend with "economic" water scarcity, where lack of technical training, bad governments or weak finances limit access even though sufficient supplies are available.



5W INFOGRAPHICS, SOURCE: INTERNATIONAL WATER MANAGEMENT INSTITUTE, *WATER FOR FOOD, WATER FOR LIFE*, 2007 (*landscape/ocean wedge*); LUCY READING-IKKANDA, SOURCE: INTERNATIONAL WATER MANAGEMENT INSTITUTE (*map*); 5W INFOGRAPHICS, SOURCE: MALIN FALKENMARK *Stockholm International Water Institute* (*water cube*)



The minimum water each person requires for drinking, hygiene and growing food. The volume is equivalent to two fifths of an Olympic-size swimming pool.

ing freshwater and to secure more of it are known; I will discuss several that seem particularly effective. What is needed now is action. Governments and authorities at every level have to formulate and execute concrete plans for implementing the political, economic and technological measures that can ensure water security now and in the coming decades.

Sources of Shortages

Solving the world's water problems requires, as a start, an understanding of how much freshwater each person requires, along with knowledge of the factors that impede supply and increase demand in different parts of the world. Malin Falkenmark of the Stockholm International Water Institute and other experts estimate that, on average, each person on the earth needs a minimum of 1,000 cubic meters (m^3) of water per year—equivalent to two fifths of the volume of an Olympic-size swimming pool—for drinking, hygiene and growing food for sustenance. Whether people get enough depends greatly on where they live, because the distribution of global water resources varies widely.

Providing adequate water is especially challenging in drier, underdeveloped and developing nations with large populations, because demand in those areas is high and supply is low. Rivers such as the Nile, the Jordan, the Yangtze and the Ganges are not only overtaxed, they also now regularly peter out for long periods during the year. And the levels of the underground aquifers below New Delhi, Beijing and many other burgeoning urban areas are falling.

Shortages of freshwater are meanwhile growing more common in developed countries as well. Severe droughts in the U.S., for instance, have

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recently left many cities and towns in the northern part of Georgia and large swaths of the Southwest scrambling for water. Emblematic of the problem are the man-made lakes Mead and Powell, both of which are fed by the overstressed Colorado River. Every year the lakes record their ongoing decline with successive, chalky high-water marks left on their tall canyon walls like so many bathtub rings.

Golden Rule

Location, of course, does not wholly determine the availability of water in a given place: the ability to pay plays a major role. People in the American West have an old saying: "Water usually runs downhill, but it always runs uphill to money." In other words, when supplies are deficient, the powers that be typically divert them to higher-revenue-generating activities at the expense of lower-revenue-generating ones. So those with the money get water, while others do not.

Such arrangements often leave poor people and nonhuman consumers of water—the flora and fauna of the adjacent ecosystems—with insufficient allocations. And even the best intentions can be distorted by the economic realities described by that Western aphorism.

A case in point occurred in one of the best-managed watersheds (or catchments) in the world, the Murray-Darling River Basin in southeast Australia. Decades ago the agriculturalists and the government there divided up the waters among the human users—grape growers, wheat farmers and sheep ranchers—in a sophisticated way based on equity and economics. The regional water-planning agreement allowed the participants to trade water and market water rights. It even reserved a significant part of the aqueous resource for the associated ecosystems and their natural inhabitants, key "users" that are often ignored even though their health in large measure underlies the well-being of their entire region. Water and marsh plants, both macro and micro, for example, often do much to remove human-derived waste from the water that passes through the ecosystems in which they live.

It turns out, however, that the quantities of water that the planners had set aside to sustain the local environment were inadequate—an underestimation that became apparent during periodic droughts—in particular, the one that has wrought havoc in the area for the last half a dozen years. The territory surrounding the Murray-Darling Basin area dried out and then burned away in tremendous wildfires in recent years.

The economic actors had all taken their share reasonably enough; they just did not consider the needs of the natural environment, which suffered greatly when its inadequate supply was reduced to critical levels by drought. The members of the Murray-Darling Basin Commission are now frantically trying to extricate themselves from the disastrous results of their misallocation of the total water resource.

Given the difficulties of sensibly apportioning the water supply within a single nation, imagine the complexities of doing so for international river basins such as that of the Jordan River, which borders on Lebanon, Syria, Israel, the Palestinian areas and Jordan, all of which have claims to the shared, but limited, supply in an extremely parched region. The struggle for freshwater has contributed to civil and military disputes in the area. Only continuing negotiations and compromise have kept this tense situation under control.

[THE AUTHOR]

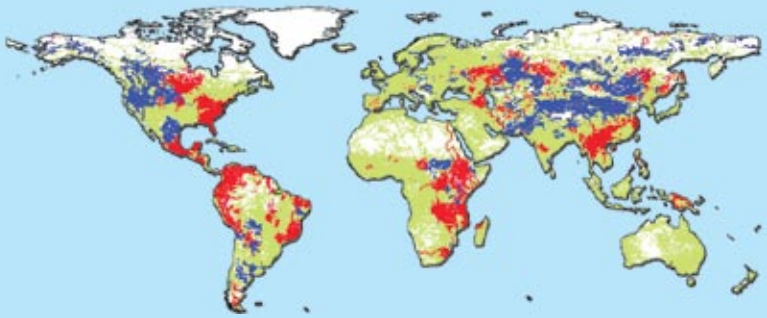
Peter Rogers is Gordon McKay Professor of Environmental Engineering and professor of city and regional planning at Harvard University, from which he received his Ph.D. in 1966. Rogers is a senior adviser to the Global Water Partnership, an organization devoted to improving global water-management practices, as well as a recipient of Guggenheim and Twentieth Century Fund fellowships.

[A LOOMING CRISIS]

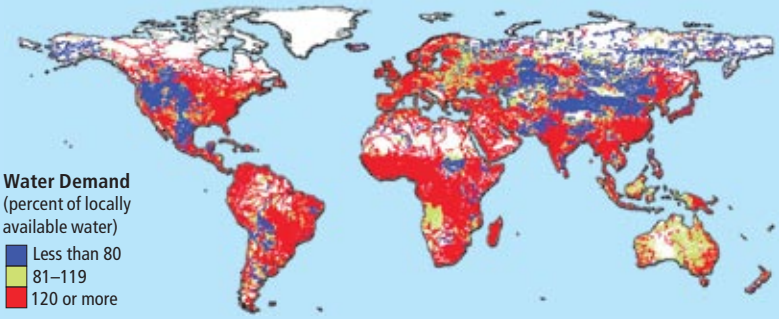
Pressure from Climate and Population Growth

Models examining the effects of climate change and of population and economic growth on water availability by 2025 indicate that climate change alone will bring scarcity to many places (*top*). Population growth, however, is even more dangerous. In the absence of concerted action to save water, the combination of population growth and climate change (*bottom*) will create scarcity far and wide.

CLIMATE CHANGE WILL INFLUENCE SCARCITY …



… BUT POPULATION GROWTH WITH CLIMATE CHANGE COULD BE DEVASTATING



PETER ROGERS (*author*); SOURCE: "GLOBAL WATER RESOURCES: VULNERABILITY FROM CLIMATE CHANGE AND POPULATION GROWTH," BY CHARLES J. VÖRÖSMARTY ET AL., IN *SCIENCE*, VOL. 289; JULY 14, 2000 (*maps*)

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WATER WITHDRAWALS from the Colorado River to green nearby desert localities such as Las Vegas (*top*) have so intensified that white mineral stains mark the high-water levels on the canyon walls surrounding Lake Mead (*bottom*), the largest man-made lake and reservoir in the U.S.

ROBERT CAMERON *Getty Images (top)*; CHRISTOPHER MORRIS *Corbis (bottom)*

Determining Demand

Like supply, demand for water varies from place to place. Not only does demand rise with population size and growth rate, it also tends to go up with income level: richer groups generally consume more water, especially in urban and industrial areas. The affluent also insist on services such as wastewater treatment and intensive farm irrigation. In many cities, and in particular in the more densely populated territories of Asia and Africa, water demands are growing rapidly.

In addition to income levels, water prices help to set the extent of demand. For example, in the late 1990s, when my colleagues and I simulated global water use from 2000 until 2050, we found that worldwide water requirements would rise from 3,350 cubic kilometers (km^3)—roughly equal to the volume of Lake Huron—to 4,900 km^3 if income and prices remained as they were in 1998. (A cubic kilometer of water is equivalent to the volume of 400,000 Olympic swimming pools.) But the demand would grow almost threefold (to 9,250 km^3) if the incomes of the poorest nations were to continue to climb to levels equivalent to those of middle-income countries today and if the governments of those nations were to pursue no special policies to restrict water use. This increased requirement would greatly intensify the pressure on water supplies, a result that agrees fairly well with forecasts made by the International Water Management Institute (IWMI) when it considered a "business-as-usual," or "do-nothing-different," scenario in the 2007 study *Water for Food, Water for Life*.

To a great extent, the technologies and policy tools required to conserve existing freshwater and secure more of it are known. What is needed now is ACTION.

Ways to Limit Waste

Given the importance of economics and income in water matters, it is clear that reasonable pricing policies that promote greater conservation by domestic and industrial users are worth adopting. In the past the cost of freshwater in the U.S. and other economic powers has been too low to encourage users to save water: as often happens when people exploit a natural resource, few worry about waste if a commodity is so cheap that it seems almost free.

Setting higher prices for water where possible is therefore near the top of my prescription list. It makes a lot of sense in developed nations, particularly in large cities and industrial areas, and more and more in developing ones as well. Higher water prices can, for instance, spur the adoption of measures such as the systematic reuse of used water (so-called gray water) for nonpotable applications. It can also encourage water agencies to build recycling and reclamation systems.

Raising prices can in addition convince municipalities and others to reduce water losses by improving maintenance of water-delivery systems. One of the major consequences of pricing water too low is that insufficient funds are generated for future development and preventive upkeep. In 2002 the U.S. Government Accountability Office reported that many domestic water utilities defer infrastructure maintenance so that they can remain within their limited operating budgets. Rather than avoiding major failures by detecting leaks early on, they usually wait until water mains break before fixing them.

The cost of repairing and modernizing the

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water infrastructures of the U.S. and Canada to reduce losses and ensure continued operation will be high, however. The consulting firm Booz Allen Hamilton has projected that the two countries will need to spend $3.6 trillion combined on their water systems over the next 25 years.

When the goal is to save water, another key strategy should be to focus on the largest consumers. That approach places irrigated agriculture in the bull's-eye: compared with any other single activity, conserving irrigation flows would conserve dramatically more freshwater. To meet world food requirements in 2050 without any technological improvements to irrigated agriculture methods, farmers will need a substantial rise in irrigation water supplies (an increase from the current 2,700 to 4,000 km^3), according to the IWMI study.

On the other hand, even a modest 10 percent rise in irrigation efficiency would free up more water than is evaporated off by all other users. This goal could be achieved by stopping up leaks in the water-delivery infrastructure and by implementing low-loss storage of water as well as more efficient application of water to farm crops.

An agreement between municipal water suppliers in southern California and nearby irrigators in the Imperial Irrigation District illustrates one creative conservation effort. The municipal group is paying to line leaky irrigation canals with waterproof materials, and the water that is saved will go to municipal needs.

An additional approach to saving irrigation water involves channeling water that is eventually intended for crop fields to underground storage in the nongrowing season. In most parts of the world, rainfall and snow accumulation—and runoff to rivers—peak during the nongrowing seasons of the year, when demand for irrigation water is lowest. The fundamental task for managers is therefore to transfer water from the high-supply season to the high-demand season when farmers need to irrigate crops.

The most common solution is to hold surface water behind dams until the growing season, but the exposure evaporates much of this supply. Underground storage would limit evaporation loss. For such storage to be feasible, engineers would first have to find large subsurface reservoirs that can be recharged readily by surface supplies and that can easily return their contents aboveground when needed for irrigation. Such "water banks" are currently operating in Arizona, California and elsewhere.

More extensive use of drip-irrigation systems, which minimize consumption by allowing water to seep in slowly either from the soil surface or directly into the root zone, would also do much to stem demand for irrigation water. Investments in new crop varieties that can tolerate low water levels and drought, as well as brackish and even saline water, could also help reduce requirements for irrigation water.

Given the rising demand for agricultural products as populations and incomes grow, it is unlikely that water managers can significantly lower the quantity of water now dedicated to irrigated agriculture. But improvements in irrigation efficiency as well as crop yields can help hold any increases to reasonable levels.

[AGRICULTURAL ACTION]

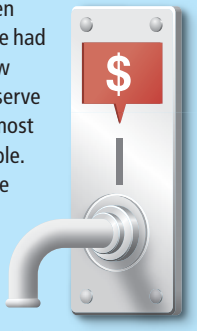
Conserve Irrigation Water

Farm irrigation eats up huge quantities of water; a 10 percent drop in irrigation water would save more than is used by all other consumers. Plugging leaks in the irrigation water-delivery system, banking water underground to limit evaporation, applying drip-irrigation methods and modifying crops to withstand less moisture could do the trick. Below, water from the Colorado River flows in an open irrigation canal in California's famed Imperial Valley croplands.

[FINANCIAL FIX]

Charge More for Water

Freshwater in the U.S. and other economic powers has traditionally been priced so low that users have had little incentive to save it. Few people take the time to conserve a commodity that seems almost free—no matter how valuable. Higher prices would promote conservation as well as investment in less wasteful water infrastructures.



11 cubic meters

The amount of water it takes to produce a pair of denim jeans. This quantity equals the capacity of a standard-size tank truck.

ON THE WEB

A person's water footprint is the volume of freshwater the individual uses directly and in the production of the goods and services he or she consumes.
Find your water footprint at:
www.waterfootprint.org

BOB ROWAN *Progressive Image/Corbis (canal)*; SW INFOGRAPHICS *(spigot and tank truck)*

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WATER INVESTMENT NEEDS, BY AREA

2005–2030 (trillions of dollars)

9.0 Asia/Oceania
5.0 South/Latin America
4.5 Europe
3.6 U.S./Canada
0.2 Africa
0.2 Middle East

Maintenance of the water infrastructure is crucial to prevent deterioration, leaks and outright breaches. At the same time, growing populations and those becoming more affluent need new, efficient water-delivery systems. To help conserve freshwater supplies, developed nations and some less developed ones will have to spend trillions of dollars on maintaining and creating efficient infrastructures during the next quarter of a century.

More Steps to Take

Keeping the demand for irrigation water in arid and semiarid areas down while still meeting the world's future food requirements can be supported by supplying "virtual water" to those places. The term relates to the amount of water expended in producing food or commercial goods. If such products are exported to a dry region, then that area will not have to use its own water to create them. Hence, the items represent a transfer of water to the recipient locale and supply them with so-called virtual water.

The notion of virtual water may sound initially like a mere accounting device, but provision of goods—and the virtual-water content of those goods—is helping many dry countries avoid using their own water supplies for growing crops, thus freeing up large quantities for other applications. The virtual-water concept and expanded trade have also led to the resolution of many international disputes caused by water scarcity. Imports of virtual water in products by Jordan have reduced the chance of water-based conflict with its neighbor Israel, for example.

The magnitude of annual global trade in virtual water exceeds 800 billion m^3 of water a year; the equivalent of 10 Nile Rivers. Liberalizing trade of farm products and reducing tariff restrictions that now deter the flow of foodstuffs would significantly enhance global virtual-water flows. Truly free farm trade, for instance, would double the current annual total delivery of virtual water to more than 1.7 trillion m^3.

[PROXY TRADE REMEDY]

Ship "Virtual Water"

Virtual water is the amount of water that is used to produce food or another product and is thus essentially embedded in the item. A kilogram of wheat, for instance, takes about 1,000 liters of water to make, so each kilogram "contains" that quantity. Export-trade shipments of wheat to an arid country means that the inhabitants will not have to expend water on wheat, which eases pressure on local supplies.

Whatever benefits the world may accrue from virtual-water transfers, the populations of growing cities need real, flowing water to drink, as well as for hygiene and sanitation. The ever expanding demand for urban, water-based sanitation services can be reduced by adopting dry, or low-water-use, devices such as dry composting toilets with urine separation systems. These technologies divert urine for reuse in agriculture and convert the remaining waste on-site into an organic compost that can enrich soil. Operating basically like garden compost heaps, these units employ aerobic microbes to break down human waste into a nontoxic, nutrient-rich substance. Farmers can exploit the resulting composted organic matter as crop fertilizer. These techniques can be used safely, even in fairly dense urban settings, as exemplified by installations at the Gebers Housing Project in a suburb of Stockholm and many other pilot projects.

Essentially, civil engineers can employ this technology to decouple water supplies from sanitation systems, a move that could save significant amounts of freshwater if it were more widely employed. Moreover, recycled waste could cut the use of fertilizer derived from fossil fuels.

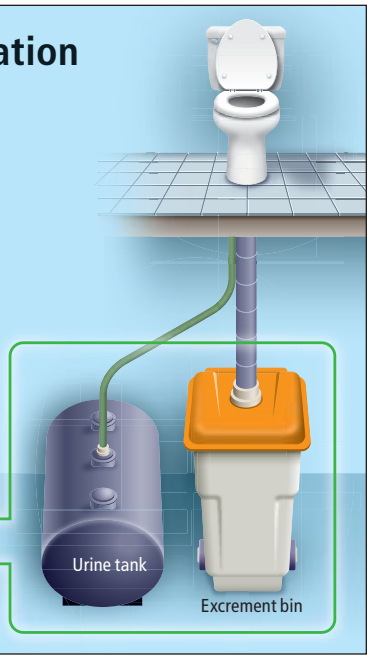
Beyond constraining demand for freshwater, the opposite approach, increasing its supply, will be a critical component of the solution to water shortages. Some 3 percent of all the water on the earth is fresh; all the rest is salty. But desalination tools are poised to exploit that huge source of salty water. A recent, substantial reduction in the costs for the most energy-efficient desalination technology—membrane reverse-osmosis

[PLUMBING PLAN]

Adopt Low-Water Sanitation

Urban and suburban sanitation services soak up plenty of water, some 100 cubic kilometers worldwide. Low-water-use toilets could make a big dent. Residents of the Gebers Housing Project in suburban Stockholm are demonstrating a system that operates like a garden composter. The system first separates excrement from urine, which is used as liquid farm fertilizer, and the remainder is recycled into fertilizer by microorganisms in a compost bin. Such technology can be safe, even in fairly dense cities and suburbs.

Treated urine is used as fertilizer in farming. When full, the excrement bins are transported to composting sites.



SOURCE: BOOZ ALLEN HAMILTON (*infrastructure investment box*); SW INFOGRAPHICS (*plumbing* and *watering can*)

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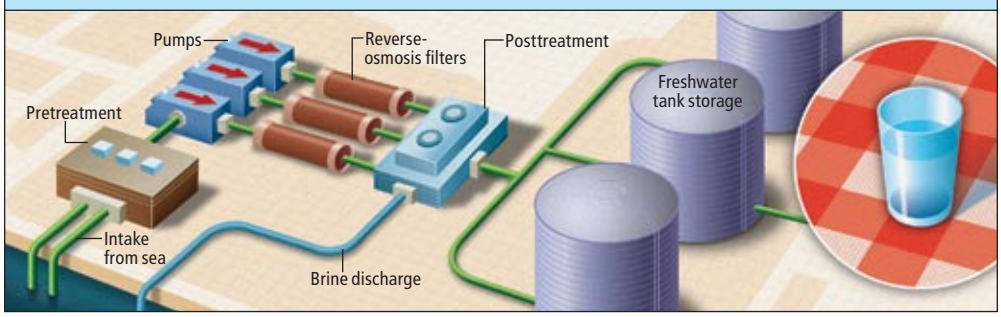
[SUPPLY-SIDE SOLUTION]

Exploit Advanced Desalination Technology

Ninety-seven percent of the world's water is salty. New lower-cost desalination plants could expand freshwater supplies for coastal population centers. Essentially, pressure is applied to salty water (*left*) so that water molecules within it pass through a selective membrane, yielding freshwater on the other side (*right*). Although the filter process tends to be power-hungry, next-generation membranes, energy-recovery techniques and other innovations could help save energy.



systems—means that many coastal cities can now secure new sources of potable water.

During reverse osmosis, salty water flows into the first of two chambers that are separated by a semipermeable (water-passing) membrane. The second chamber contains freshwater. Then a substantial amount of pressure is applied to the chamber with the salt solution in it. Over time the pressure forces the water molecules through the membrane to the freshwater side.

Engineers have achieved cost savings by implementing a variety of upgrades, including better membranes that require less pressure, and therefore energy, to filter water and system modularization, which makes construction easier. Large-scale desalination plants using the new, more economical technology have been built in Singapore and Tampa Bay, Fla.

Scientists are now working on reverse-osmosis filters composed of carbon nanotubes that offer better separation efficiencies and the potential of lowering desalination costs by an additional 30 percent. This technology, which has been demonstrated in prototypes, is steadily approaching commercial use. Despite the improvements in energy efficiency, however, the applicability of reverse osmosis is to some degree limited by the fact that the technology is still energy-intensive, so the availability of affordable power is important to significantly expanding its application.

A Return on Investment

Not surprisingly, staving off future water shortages means spending money—a lot of it. Analysts at Booz Allen Hamilton have estimated that to provide water needed for all uses through 2030, the world will need to invest as much as $1 trillion a year on applying existing technologies for conserving water, maintaining and replacing infrastructure, and constructing sanitation systems. This is a daunting figure to be sure, but perhaps not so huge when put in perspective. The required sum turns out to be about 1.5 percent of today's annual global gross domestic product, or about $120 per capita, a seemingly achievable expenditure.

Unfortunately, investment in water facilities as a percentage of gross domestic product has dropped by half in most countries since the late 1990s. If a crisis arises in the coming decades, it will not be for lack of know-how; it will come from a lack of foresight and from an unwillingness to spend the needed money.

There is, however, at least one cause for optimism: the most populous countries with the largest water infrastructure needs—India and China—are precisely those that are experiencing rapid economic growth. The part of the globe that is most likely to continue suffering from inadequate water access—Africa and its one billion inhabitants—spends the least on water infrastructure and cannot afford to spend much; it is crucial, therefore, that wealthier nations provide more funds to assist the effort.

The international community can reduce the chances of a global water crisis if it puts its collective mind to the challenge. We do not have to invent new technologies; we must simply accelerate the adoption of existing techniques to conserve and enhance the water supply. Solving the water problem will not be easy, but we can succeed if we start right away and stick to it. Otherwise, much of the world will go thirsty. ■

CONSERVATION: DRIP BY DRIP

Doing small things consistently over time—if enough people participate—can make a dent in global problems. Here are a few suggestions. Find more lists of easy ways to conserve water and all kinds of water facts at www.SciAm.com/aug2008

- Start a compost pile rather than using an in-sink garbage disposal unit.
- Run your high-efficiency (Energy Star) washing machine or dishwasher for full loads only.
- Install a dual-flush toilet (which uses less water for liquid waste) or low-flow unit and a gray-water recycling system.
- Use a low-flow showerhead and capture bathwater to water plants.
- Water your lawn in the early morning or at night to avoid losses from evaporation.

MORE TO EXPLORE

Balancing Water for Humans and Nature: The New Approach in Ecohydrology. Malin Falkenmark and Johan Rockström. Earthscan Publications, 2004.

Water Crisis: Myth or Reality? Edited by Peter P. Rogers, M. Ramón Llamas and Luis Martínez-Cortina. Taylor & Francis, 2006.

The World's Water 2006–2007: The Biennial Report on Freshwater Resources. Peter H. Gleick et al. Island Press, 2006.

Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture. Edited by David Molden. Earthscan (London) and International Water Management Institute (Colombo), 2007. Available at **www.iwmi.cgiar.org/Assessment**

5W INFOGRAPHICS

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Why Migraines Strike

Biologists finally are unraveling the medical mysteries of migraine, from aura to pain

By David W. Dodick and J. Jay Gargus

KEY CONCEPTS

- Migraine is more than a headache: it is intensely painful and has distinct phases.
- The disorder used to be considered a vascular one, but recent research reveals it to be neurological, related to a wave of nerve cell activity that sweeps across the brain.
- The root of migraine may reside in brain stem malfunctioning.
- Although debate swirls about the precise cause of migraine, discoveries are already permitting the development of new treatments. *—The Editors*

For the more than 300 million people who suffer migraines, the excruciating, pulsating pain that characterizes these debilitating headaches needs no description. For those who do not, the closest analogous experience might be severe altitude sickness: nausea, acute sensitivity to light, and searing, bed-confining headache. "That no one dies of migraine seems, to someone deep into an attack, an ambiguous blessing," wrote Joan Didion in the 1979 essay "In Bed" from her collection *The White Album*.

Historical records suggest the condition has been with us for at least 7,000 years, yet it continues to be one of the most misunderstood, poorly recognized and inadequately treated medical disorders. Indeed, many people seek no medical care for their agonies, most likely believing that doctors can do little to help or will be downright skeptical and hostile toward them. Didion wrote "In Bed" almost three decades ago, but some physicians remain as dismissive today as they were then: "For I had no brain tumor, no eyestrain, no high blood pressure, nothing wrong with me at all: I simply had migraine headaches, and migraine headaches were, as everyone who did not have them knew, imaginary."

Migraine is finally starting to get the attention it deserves. Some of that attention is the result of epidemiological studies revealing just how common these headaches are and how incapacitating: a World Health Organization report described migraine as one of the four most disabling chronic medical disorders. Additional concern results from recognition that such headaches and their aftermaths cost the U.S. economy $17 billion a year in lost work, disability payments and health care expenses. But most of the growing interest comes from new discoveries in genetics, brain imaging and molecular biology. Though of very different natures, those findings seem to converge and reinforce one another, making researchers hopeful that they can get to the bottom of migraine's causes and develop improved therapies to prevent them or halt them in their tracks.

The Ascent of Vapors

Any plausible explanation of migraine needs to account for a wide and varied set of symptoms. The frequency, duration, experience and catalysts of episodes differ greatly. Victims have, on average, one or two daylong attacks every month. But 10 percent get them weekly, 20 percent experience them for two to three days, and up to 14 percent have them more than 15 days a month. Often the pain strikes just one side of the head, but not always. Migraines in people prone to them can be set in motion by such a variety of events that they seem inescapable; alcohol, dehydration, physical exertion, menstruation, emotional stress, weather changes, seasonal changes, allergies, sleep deprivation, hunger, altitude and fluorescent lights are all cited as triggers. Migraines occur in all ages and both genders, yet women between the ages of 15 and 55 are disproportionately hit—two thirds of cases occur in this population.

Physicians over the years have proposed many reasons for why these headaches arise. Galen in ancient Greece attributed them to the ascent of vapors, or humors, from the liver to the head. Galen's description of hemicrania—a painful disorder affecting approximately one half of the head—is indeed what we refer to as migraine today: the old word "hemicrania" eventually became "megrim" and ultimately "migraine."

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[BASICS]

FOUR PHASES OF MIGRAINE

Unlike most headaches, migraine has distinct stages, although not all sufferers experience each one—a perplexing facet of the disorder.

60%	**PRODROME** TYPICAL FEATURES: Difficulty concentrating, yawning, fatigue, and sensitivity to light and noise. DURATION: A few hours to a few days
30%	**AURA** TYPICAL FEATURES: Visual illusions of sparks and lights, often followed by blind or dark spots in the same configuration as the earlier bright hallucinations. DURATION: 20 to 60 minutes
100%	**HEADACHE** TYPICAL FEATURES: Excruciating pain accompanied by sensitivity to light and sound, nausea and vomiting. Sometimes the pain affects half the head. DURATION: 4 to 72 hours
70%	**POSTDROME** TYPICAL FEATURES: Persistence of sensitivity to light and movement, as well as lethargy, fatigue and difficulty focusing; some patients describe this as a "zombie" phase. DURATION: A few hours to a few days

Percentage who report undergoing each phase

Blood flow replaced humors as the culprit in the 17th century, and this vascular hypothesis held sway, with few exceptions, until the 1980s. The accepted idea, based on the observations and inferences of several physicians, including Harold G. Wolff of New York–Presbyterian Hospital, was that migraine pain stems from the dilation and stretching of brain blood vessels, leading to the activation of pain-signaling neurons. Wolff thought the headache was preceded by a drop in blood flow brought about by the constriction of these same blood vessels.

Fresh observations from brain scans have altered understanding of the vascular changes. It turns out that in many the pain is preceded not by a decrease in blood flow but by an *increase*—an increase of about 300 percent. During the headache itself, though, blood flow is not increased; in fact, circulation appears normal or even reduced. Not only has the specific understanding of blood flow changed, but so has the prevailing view of the root of migraine. Migraine is now thought to arise from a disorder of the nervous system—and likely from the most ancient part of that system, the brain stem.

Aura's Origin

This newer insight has come mainly from studying two aspects of migraine: the aura, which precedes the pain in 30 percent of sufferers, and the headache itself. The term "aura" has been used for nearly 2,000 years to describe the sensory hallucinations immediately preceding some epileptic seizures; for 100 years or so, it has also been used to describe the onset of many migraines. (Epilepsy may occur in people with migraine, and vice versa; the reasons are under investigation.) The most common form of aura is a visual illusion of brilliant stars, sparks, flashes of light, lightning bolts or geometric patterns, which are often followed by dark spots in the same shape as the original bright image. For some people, the aura can include a feeling of tingling or weakness, or both, on one side of the body as well as speech impairment. Usually the aura precedes the headache, but it may start after the pain begins and persist through it.

Aura appears to stem from cortical spreading depression—a kind of "brainstorm" anticipated as the cause of migraine in the writings of 19th-century physician Edward Lieving. Although biologist Aristides Leão first reported the phenomenon in animals in 1944, it was experimentally linked to migraine only recently. In more technical terms, cortical spreading depression is a wave of intense nerve cell activity that spreads through an unusually large swath of the cortex (the furrowed, outer layer of the brain), especially the areas that control vision. This hyperexcitable phase is followed by a wave of widespread, and relatively prolonged, neuronal inhibition. During this inhibitory phase, the neurons are in a state of "suspended animation," during which they cannot be excited.

Neuronal activity is controlled by a carefully synchronized flow of sodium, potassium and calcium ions across the nerve cell membrane through channels and pumps. The pumps keep resting cells high in potassium and low in sodium and calcium. A neuron "fires," releasing neurotransmitters, when the inward flow of sodium and calcium through opened channels depolarizes the membrane—that is, when the inside of the cell becomes positively charged relative to the outside. Normally, cells then briefly hyperpolarize: they become strongly negative on the inside relative to the outside by allowing potassium ions to rush out. Hyperpolarization closes the sodium and calcium channels and returns the neurons to their resting state soon after firing. But neurons can remain excessively hyperpolarized, or inhibited, for a long time following intense stimulations.

The phases of hyperexcitability followed by inhibition that characterize cortical spreading depression can explain the changes in blood flow that have been documented to occur before

VARIABILITY

Victims experience attacks for different durations and at different frequencies. Most have migraines one or two days every month. But 10 percent have them weekly, and up to 14 percent get them more than 15 days every month. Two thirds of the world's 300 million migraine sufferers are women aged 15 to 55—suggesting estrogen plays a role.

SUSAN MADDEN

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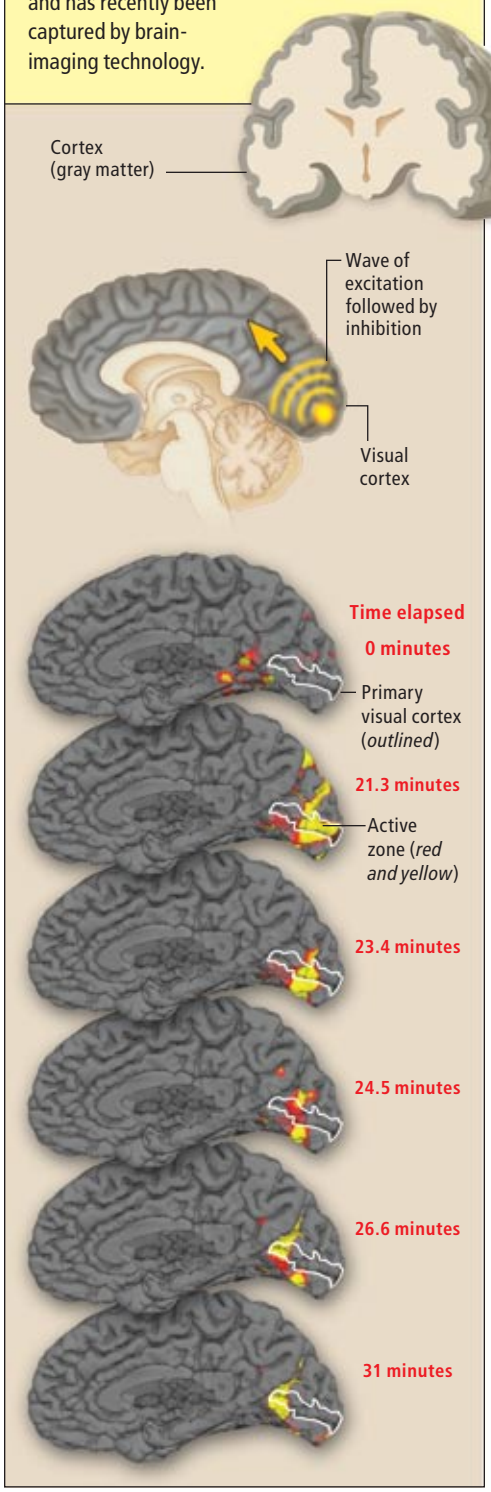
[WHAT CAUSES AURAS]

A BRAINSTORM

Auras have been found to stem from cortical spreading depression: a wave of excessive signaling across large areas of the brain, followed by abnormal silence in the previously overactive areas. The spreading moves across the cortex at the rate of two to three millimeters a minute and has recently been captured by brain-imaging technology.



COURTESY OF DAVID W. DODICK (*Dodick*); UNIVERSITY OF CALIFORNIA, IRVINE, MEDICAL CENTER (*Gargus*); TAMI TOLPA (*brain illustrations*); COURTESY OF NOUCHINE HADJIKHANI (*brain scans*); MIGRAINE ACTION ASSOCIATION AND BOEHRINGER INGELHEIM (*aura art*)

migraine pain sets in. When neurons are active and firing, they require a great deal of energy and, thus, blood—just what investigators see during brain scans of patients experiencing aura. But afterward, during inhibition, the quiet neurons need less blood.

Various other observations support the idea that cortical spreading depression underlies aura. When recorded by advanced imaging technology, the timing of the depolarizing wave dovetails neatly with descriptions of aura. The electrical wave travels across the cortex at a rate of two to three millimeters a minute, and the visual illusions that accompany aura are exactly those that would arise from an activation spreading across the cortical fields at just that rate. The suite of sensations that aura can entail—visual, sensory, motor—suggest that corresponding areas of the cortex are affected in sequence as the "storm" crosses them. The dark spots that patients experience after the bright hallucinations are consistent with neuronal inhibition in the regions of the visual cortex that have just experienced the hyperexcitability.

Genetic studies have offered a clue to why cortical spreading depression occurs in some migraine sufferers. Nearly all migraine is thought to be a common complex polygenetic disorder—in the same camp as diabetes, cancer, autism, hypertension and many other disorders. Such diseases run in families. Identical twins are much more likely to share migraine than fraternal twins are, indicating a strong genetic component. But the disease is clearly not caused by a single genetic mutation; rather a person apparently becomes susceptible by inheriting mutations in a number of genes, each probably

[THE AUTHORS]

David W. Dodick (*left*) and **J. Jay Gargus** (*right*) share a deep interest in understanding and ameliorating migraine. Dodick, a professor of neurology at the Mayo Clinic in Arizona, received his medical degree at Dalhousie University in Halifax, Nova Scotia. He studies the central nervous system abnormalities behind migraine and other forms of headache. Gargus, a professor of physiology, biophysics and human genetics at the University of California, Irvine, received his medical degree and doctorate at Yale University. He is studying the genetic underpinnings of migraine and other ion channel disorders.

AURAS take different forms, and many patients have sought to represent the hallucinations in their art. This depiction of an aura highlights the brightness and jaggedness that many people experience.

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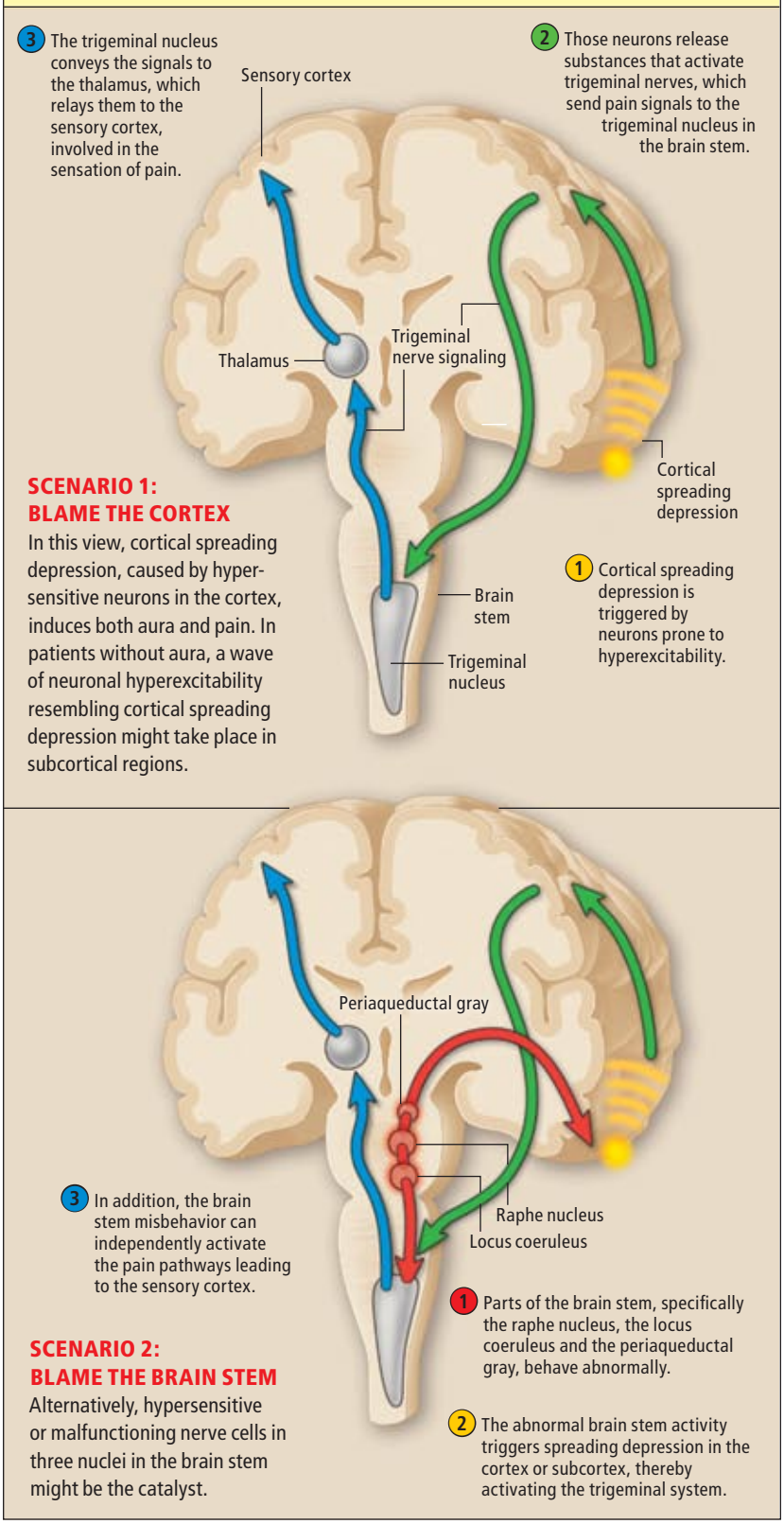
[HYPOTHESES]

THE ROOT OF MIGRAINE PAIN

Whether headache is initiated by the brain stem, by the cortex or by the subcortex remains an active debate.



TAMI TOLPA

making a small contribution. Nongenetic components operate as well, because even identical twins are "discordant" for the disorder: sometimes one twin will suffer from migraine, and the other will not.

Investigators do not know which genes increase susceptibility to migraine and its aura in the general population, but studies of people affected by a rare form of the disorder, called familial hemiplegic migraine, indicate that flaws in neuronal ion channels and pumps cause the aura and pain in these patients. Notably, three genes have been shown to carry mutations that individually are potent enough to cause the disease—and all three encode neuronal ion channels and pumps. What is more, the genes are altered by mutations that increase the excitability of nerve cells, presumably by altering the properties of the encoded ion channels and pumps. These findings strongly support the idea that migraine could be a channelopathy, a newly recognized type of disease that arises from disturbances in ion transport systems—a known cause of ailments such as cardiac arrhythmia and seizures.

It is not clear whether malfunctioning ion pumps and channels are the only means by which aura can be produced. Nor is it clear that the common forms of migraine involve perturbations in the three genes implicated in familial hemiplegic migraine. But the genetic insights remain very exciting because they suggest a relation between cortical spreading depression and ion channel problems, one that could prove crucial to designing new medications.

From Aura to Ache

At the same time that researchers have been making headway in understanding the relation between aura and cortical spreading depression, they have been probing the source of migraine pain—the headache that is felt in those who experience aura as well as those who do not. The immediate source of the pain itself is obvious. Although most regions of the brain do not register or transmit pain signals, a network of nerves called the trigeminal nerve system does. These neurons carry pain signals from the membranes that surround the brain, called the meninges, as well as from the blood vessels that infuse the membranes. Pain is relayed through the trigeminal network to an area called the trigeminal nucleus in the brain stem and, from there, can be conveyed up through the thalamus to the sensory cortex, which is involved in our

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awareness of pain and other senses. What first activates the trigeminal nerves in migraine, however, is under debate. There are essentially two schools of thought.

Some researchers contend that cortical spreading depression directly stimulates the trigeminal nerves. As the wave of hyperexcitability travels across the cortex, it brings about the release of neurotransmitters, such as glutamate and nitric oxide, as well as of ions. These chemicals serve as messengers that induce the trigeminal nerves to transmit pain signals. Researchers have observed in animals that cortical spreading depression does indeed activate the trigeminal nerves in this way.

That pathway to pain could even explain what happens in patients who do not experience aura. According to this view, cortical spreading depression might occur in areas of the cortex whose activation produces no outward symptoms before the onset of pain. Or spreading depression might occur in subcortical regions in certain people and stimulate the trigeminal nerves. In this case, although patients may not experience aura, the basic physiology would be the same as in those who do. Good evidence supports this hypothesis. Spreading depression can be evoked in laboratory animals in subcortical regions.

Moreover, the changes in cerebral blood flow that reflect the phases of cortical excitation and subsequent inhibition in migraine sufferers with aura have also been seen in people who experience migraine without aura; those patients, too, show a large increase in blood flow followed by normal or reduced flow. This finding raises the possibility that cortical spreading depression is fundamental to migraine but that only in some instances does it give rise to visual symptoms recognized as aura. Instead the process might generate less obvious symptoms, such as fatigue or difficulty concentrating. The finding may also explain why many people who experience aura will at times undergo attacks without it.

Other investigators place the root of migraine pain not in cortical or subcortical spreading depression but in the brain stem—Grand Central Station for information passing to and from the body and the brain. It is also home to the control center for alertness, perception of light and noise, cerebral blood flow, respiration, sleep-wake cycles, cardiovascular function and, as described earlier, pain sensitivity. Positron-emission tomography has revealed that three clusters of cells, or nuclei, in the brain stem—the locus coeruleus, raphe nucleus and periaqueductal gray—are active during and after migraine. According to this hypothesis, abnormal activity in those nuclei could induce pain in two ways. The nuclei normally inhibit trigeminal neurons within the trigeminal nucleus, continuously saying, in effect, "don't fire." The nuclei's misbehavior could impair this ability and thus allow the trigeminal neurons to fire even when the meninges send no pain signals. In that situation, the trigeminal nucleus would relay pain messages to the sensory cortex in the absence of incoming pain signals from the meninges or blood vessels. The three nuclei might also trigger spreading depression.

Researchers have noted that if one were to alter a part of the brain stem so as to bring about other symptoms of migraine as well, including aura, the place to do it would be these three nuclei. One of their most important functions is to control the flow of sensory information—such as light, noise, smell and pain—that reaches the sensory cortex. Occasional dysfunction in these clusters of cells could therefore explain why migraine sufferers may experience sensitivity to light, sound and odors.

In addition, the activity of these cells is modulated by the behavioral and emotional state of the individual—factors that can trigger migraines. These brain stem areas receive input from only two areas of the cortex, the limbic and paralimbic cortices, regions that regulate arousal, attention and mood. Through its con-

MIGRAINE has been around forever, as far as experts can tell. The 12th-century illuminated manuscript *Scivias* at the left portrays a vision described by theologian and abbess Hildegard of Bingen. It is thought to be one of the earliest representations of an aura.

ERICH LESSING *Art Resource, NY*

CATALYSTS

For unknown reasons, migraine can be set off by various triggers, including alcohol, perfume, dehydration, exercise, menstruation, stress, weather changes, seasonal changes, allergies, lack of sleep, altitude, flickering lights and hunger.

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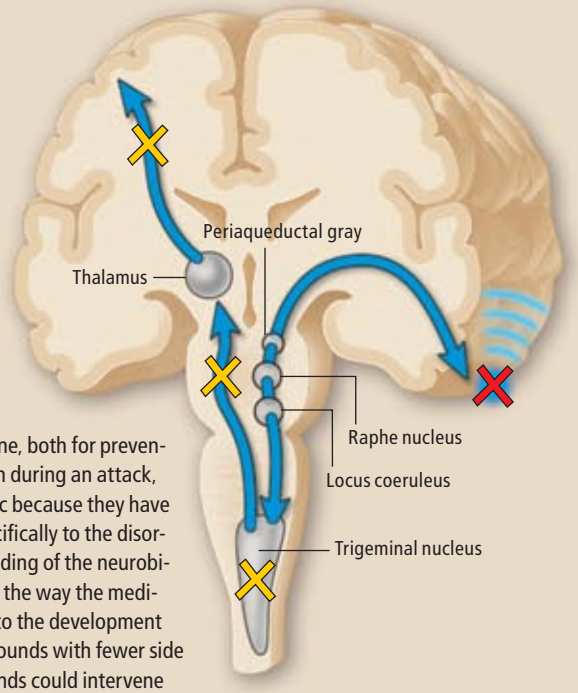
[TREATMENT]

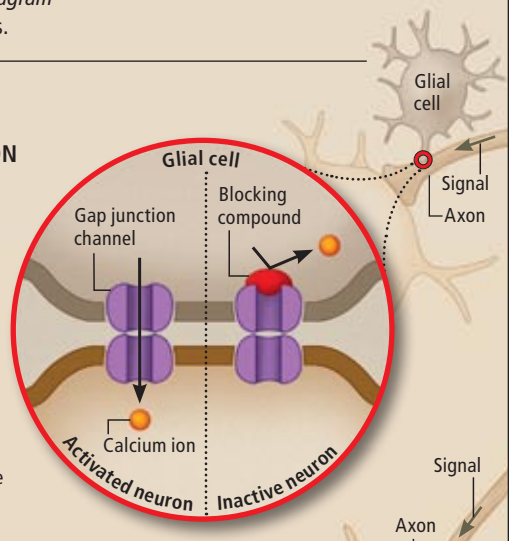
INSIGHTS REFINE THERAPIES



Treatments for migraine, both for prevention and for alleviation during an attack, have been problematic because they have not been tailored specifically to the disorder. Recent understanding of the neurobiology of migraine and the way the medicines work is leading to the development of more refined compounds with fewer side effects. Such compounds could intervene at various sites (*marked on the diagram with Xs*) and work in several ways.

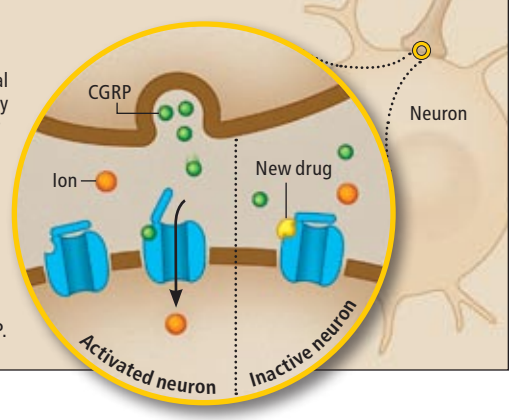
INHIBIT CORTICAL SPREADING DEPRESSION

The wave of hyperexcitability called cortical spreading depression involves ion transfer from glia (a class of brain cell) to neurons, through a form of ion channel called a gap junction. Gap junctions allow calcium to flow between glia and neurons, which activates the neurons. Compounds currently in clinical trials close these cellular pores to stop the wave in its tracks.



INHIBIT TRIGEMINAL NEURONS

One of the ways that trigeminal nerves convey pain signals is by releasing the neurotransmitter calcitonin gene–related peptide (CGRP), which activates neurons in the trigeminal nucleus. A class of drugs called triptans alleviates migraine by blocking the release of CGRP. New treatments in advanced trials block the effects of CGRP.



nection with the brain stem, the limbic cortex affects the functioning of the rest of the cortex—a fact that might explain how emotional and psychological stress could catalyze migraines, why mood fluctuates during migraine, and why there is an association between migraine and depression and anxiety disorders, both of which occur more commonly in migraine sufferers than in others.

Finally, the spontaneous, pacemakerlike activity of the raphe nucleus neurons—crucial to regulating pain pathways, circadian rhythms and sleep-wake cycles—depends on the perfect working of ion channels in neurons of that region and on the neurons' release of the neurotransmitters norepinephrine and serotonin into other brain areas. Such neurotransmission may be an ancient mechanism that is perturbed in migraine: experiments in the roundworm *Caenorhabditis elegans* have revealed that two genes very like those mutated in familial hemiplegic migraine are critical regulators of serotonin release. This finding opens the possibility that mutations in ion channels may lead to aberrant function in these brain stem areas and perhaps, as a result, to hyperexcitability in the cortical areas they influence.

The question then becomes, Does pain typically arise from the intrinsic hyperexcitability of cortical neurons (which leads to cortical spreading depression, activation of meningeal trigeminal pain fibers and the pain of a migraine)? Or does some glitch in brain stem activity incite the pain (by directly rendering the trigeminal neurons spontaneously active or by facilitating cortical spreading depression, or both)? The latter scenario is more convincing to some researchers because the pivotal control exerted by the brain stem over so many aspects of our experience could explain the varied symptoms of migraine.

What the Future May Hold

At the moment, only a few drugs can prevent migraine. All of them were developed for other diseases, including hypertension, depression and epilepsy. Because they are not specific to migraine, it will come as no surprise that they work in only 50 percent of patients—and, in them, only 50 percent of the time—and induce a range of side effects, some potentially serious.

Recent research on the mechanism of these antihypertensive, antiepileptic and antidepressant drugs has demonstrated that one of their effects is to inhibit cortical spreading depression.

TAMI TOLPA (*top*); JEN CHRISTIANSEN (*bottom*)

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The drugs' ability to prevent migraine with and without aura therefore supports the school of thought that cortical spreading depression contributes to both kinds of attacks. Using this observation as a starting point, investigators have come up with novel drugs that specifically inhibit cortical spreading depression. Those drugs are now being tested in migraine sufferers with and without aura. They work by preventing gap junctions, a form of ion channel, from opening, thereby halting the flow of calcium between brain cells.

The medicines prescribed for use during an attack have been as problematic as the ones used preventively. Triptans—as the class of drug is called—constrict blood vessels throughout the body, including coronary arteries, seriously limiting their use. These treatments were developed based on the mistaken idea that blood vessel dilation caused the pain and thus constriction was necessary to alleviate it.

It now appears that triptans ease migraine by interrupting the release of messenger molecules—specifically calcitonin gene–related peptide—from trigeminal nerves that feed signals into the trigeminal nucleus. The interruption blocks those trigeminal nerves from communicating with the brain stem's pain-transmitting network of neurons. It is also possible that triptans prevent such communication by operating in the thalamus and the periaqueductal gray.

The new understanding of triptan activity has opened up possibilities for drug development, including a focus on calcitonin gene–related peptide. Several medicines that block the action of that pain-producing neurotransmitter are in clinical trials, and they appear not to constrict arteries. In addition, researchers are devising therapies that target other trigeminal neurotransmitters, such as glutamate and nitric oxide, in a further effort to interrupt the communication between trigeminal nerves innervating the meninges and the trigeminal nucleus in the brain stem. These compounds will be the first specifically designed to combat migraine during an attack by targeting neurons without constricting blood vessels.

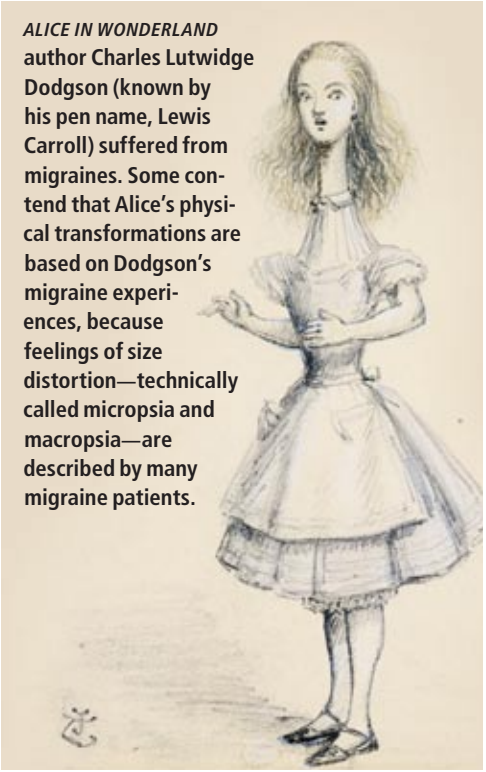
Researchers have also examined nonpharmaceutical approaches. A handheld device that transmits brief pulses of magnetic stimulation is being evaluated, for example, for the treatment of migraine with and without aura. The premise is that this technology, called transcranial magnetic stimulation, or TMS, may interrupt cortical spreading depression and possibly prevent pain from arising or progressing.

For millions of people, these developments mark a breakthrough—not only in terms of relief from pain if all goes well but also in regard to attitudes about migraine. Scientists and physicians are finally coming to see migraine for the complex, biologically fascinating process it is and to recognize its powerfully debilitating effects. The disorder is "imaginary" no longer. ■

Clues from Genetic Studies

In recent years researchers have identified several gene mutations that underlie familial hemiplegic migraine, a rare, inherited form of migraine. Although the genetic work is in early stages, it is already clear that these mutations disrupt the complex workings of the ion channels and pumps that regulate the activity of nerve cells. The genetic findings have helped convince many investigators that even common forms of migraine arise from abnormal activity by nerve cells rather than from blood-flow changes in the brain. This conclusion is reinforced by the discovery that three "migraine genes" also carry mutations that cause epilepsy, one of the first heritable diseases recognized to result from abnormal ion channel functioning. Such diseases are called channelopathies. The genes implicated in the familial disorder include those listed below:

- *CACNA1A* encodes a major protein of a neuronal calcium channel called the P/Q channel.
- *ATP1A2* carries the information for producing a protein that pumps sodium and potassium ions across the membranes of nerve cells to create the ion gradient used by ion channels.
- *SCN1A* is the most recently discovered familial hemiplegic migraine gene. It gives rise to a neuronal sodium channel.



ALICE IN WONDERLAND author Charles Lutwidge Dodgson (known by his pen name, Lewis Carroll) suffered from migraines. Some contend that Alice's physical transformations are based on Dodgson's migraine experiences, because feelings of size distortion—technically called micropsia and macropsia—are described by many migraine patients.

CHRISTIE'S IMAGES/CORBIS

MORE TO EXPLORE

Migraine. Oliver Sacks. Vintage, 1999.

Migraine—New Molecular Mechanisms. Daniela Pietrobon in *Neuroscientist,* Vol. 11, No. 4, pages 373–386; 2005.

Receptor, Transporter, and Ion Channel Diseases. J. Jay Gargus in *Encyclopedia of Molecular Cell Biology and Molecular Medicine.* Edited by Robert A. Myers. Wiley, 2005.

Chronic Daily Headache. David W. Dodick in *New England Journal of Medicine,* Vol. 354, No. 2, pages 158–165; January 12, 2006.

Recent Advances in Understanding Migraine Mechanisms, Molecules and Therapeutics. Peter J. Goadsby in *Trends in Molecular Medicine,* Vol. 13, No. 1, pages 39–44; January 2007.

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QUANTUM COMPUTING WITH IONS

Researchers are taking the first steps toward building ultrapowerful computers that use individual atoms to perform calculations

By Christopher R. Monroe and David J. Wineland

KEY CONCEPTS

- Quantum computers can store and process data using atoms, photons or fabricated microstructures. These machines may someday be able to perform feats of computing once thought to be impossible.
- The manipulation of trapped ions is at the forefront of the quantum computing effort. Researchers can store data on the ions and transfer information from one ion to another.
- Scientists see no fundamental obstacles to the development of trapped-ion computers.

—The Editors

Over the past several decades technological advances have dramatically boosted the speed and reliability of computers. Modern computer chips pack almost a billion transistors in a mere square inch of silicon, and in the future computer elements will shrink even more, approaching the size of individual molecules. At this level and smaller, computers may begin to look fundamentally different because their workings will be governed by quantum mechanics, the physical laws that explain the behavior of atoms and subatomic particles. The great promise of quantum computers is that they may be able to perform certain crucial tasks considerably faster than conventional computers can.

Perhaps the best known of these tasks is factoring a large number that is the product of two primes. Multiplying two primes is a simple job for computers, even if the numbers are hundreds of digits long, but the reverse process—deriving the prime factors—is so extraordinarily difficult that it has become the basis for nearly all forms of data encryption in use today, from Internet commerce to the transmission of state secrets. In 1994 Peter Shor, then at Bell Laboratories, showed that a quantum computer, in theory, could crack these encryption codes easily because it could factor numbers exponentially faster than any known classical algorithm could. And, in 1997, Lov K. Grover, also at Bell Labs, showed that a quantum computer could significantly increase the speed of searching an unsorted database—say, finding a name in a phone book when you have only the person's phone number.

Actually building a quantum computer, how-

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DAVID EMMITE (*computer setup*); GEORGE RETSECK (*spheres*)

ever, will not be easy. The quantum hardware—the atoms, photons or fabricated microstructures that store the data in quantum bits, or qubits—needs to satisfy conflicting requirements. The qubits must be sufficiently isolated from their surroundings; otherwise stray external interactions will halt their computations. This destructive process, known as decoherence, is the bane of quantum computers. But the qubits also have to interact strongly with one another and must ultimately be measured accurately to display the results of their calculations.

Scientists around the globe are pursuing several approaches to building the first prototype quantum computers. Our own research focuses on processing information with singly charged positive ions, atoms that have been stripped of one electron. We have trapped short strings of ions—confining the particles in a vacuum using electric fields produced by nearby electrodes—so that they can receive input signals from a laser and share data with one another. Our goal is to develop quantum computers that are scalable—that is, systems in which the number of qubits could be increased to the hundreds or thousands. Such systems would fulfill the promise of the technology by accomplishing complex processing tasks that no ordinary computer could match.

Trapping Ions

Quantum mechanics is a theory based on waves. Just as the sound waves from two or more piano strings can merge into a chord, different quantum states can be combined into a superposition. For example, an atom may be simultaneously in two locations or in two different states of excitation.

TRAPPED-ION COMPUTERS could encode and process data with strings of ions that act somewhat like the suspended metal balls in a Newton's cradle (as seen in this artist's conception). The ions interact through oscillatory motions. Researchers can manipulate the particles by training laser beams on them.

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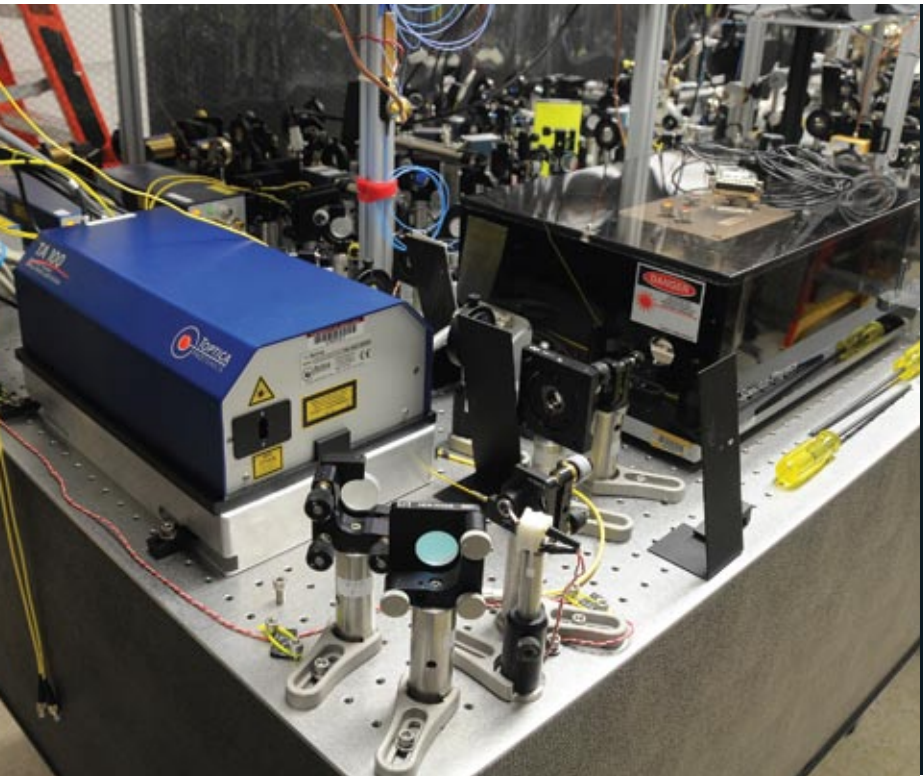
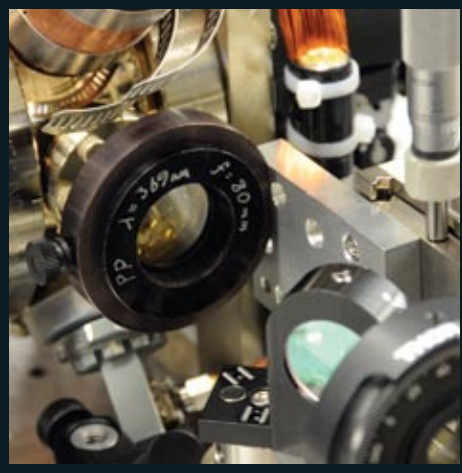




TABLETOP EXPERIMENTS have shown the feasibility of quantum information processing. Researchers use lasers (*blue device in photograph at left*) to generate beams that are shunted by mirrors across the table to the apparatus containing the trapped ion (*above*). The laser cools the ion, draining away its kinetic energy so that investigators can easily manipulate it.

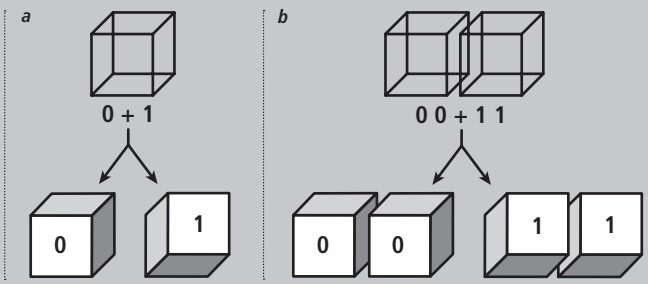
When a quantum particle in a superposition state is measured, the conventional interpretation is that the state collapses to a single result, with the probability of each possible measurement given by the relative proportions of the waves in the superposition [*see box below*]. The potential power of a quantum computer derives from these superpositions: unlike a conventional digital bit, which can have a value of either 0 or 1, a qubit can be both 0 and 1 at the same time. A system with two qubits can hold four values simultaneously—00, 01, 10 and 11. In general, a quantum computer with N qubits can simultaneously manipulate 2^N numbers; a collection of only 300 atoms, each storing a quantum bit, could hold more values than the number of particles in the universe!

These larger quantum superpositions are usually entangled, meaning that the measurements of the individual qubits will be correlated. Quantum entanglement can be thought of as an invisible wiring between particles that cannot be replicated in classical physics, a wiring that Einstein called "spooky action at a distance." In our trapped-ion experiments, for example, each electrically levitated ion behaves like a microscopic bar magnet; the qubit states of 1 and 0 can correspond to two possible orientations of each atomic magnet (say, up and down). Laser cooling, which drains kinetic energy from atoms by scattering photons, brings the ions almost to rest within the trap. Because the ions reside in a vacuum chamber, they are isolated from the

[ENTANGLEMENT]

SPOOKY ACTION AT A DISTANCE

The "ambiguous cube" (*a*) is like an ion in a superposition state—a measurement of the ion will lock it into one of two definite states (0 or 1). When two ions are in an entangled superposition (*b*), a measurement will force both ions into the same state (either 0 or 1) even though there is no physical connection between them.



[THE AUTHORS]

Christopher R. Monroe (*left*) is Bice Sechi-Zorn Professor of Physics at the University of Maryland and Fellow of the Joint Quantum Institute at Maryland and the National Institute of Standards and Technology (NIST). Monroe specializes in the electromagnetic trapping, laser cooling and quantum control of atoms and ions. **David J. Wineland** (*right*), who received his B.A. from the University of California, Berkeley, in 1965 and his Ph.D. from Harvard University in 1970, is leader of the Ion-Storage Group in NIST's Time and Frequency Division in Boulder, Colo. The group has focused on laser cooling and spectroscopy of trapped atomic ions.

JOINT QUANTUM INSTITUTE (*optical tables*); JENS ZORN (*Monroe*); EDIE DEWEESE (*Wineland*); JEN CHRISTIANSEN (*illustrations*). SOURCE: *TAKING THE QUANTUM LEAP*, BY FRED ALAN WOLF (*bottom*)

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environment, yet the electric repulsion among them provides a strong interaction for producing entanglement. And laser beams thinner than a human hair can be targeted on individual atoms to manipulate and measure the data stored in the qubits.

Over the past few years scientists have performed many of the proof-of-principle experiments in quantum computing with trapped ions. Researchers have produced entangled states of up to eight qubits and have shown that these rudimentary computers can run simple algorithms. It appears straightforward (though technically very challenging) to scale up the trapped-ion approach to much larger numbers of qubits. Taking the lead from classical computers, this effort would involve sequencing a few types of quantum logic gates, each made up of only a few trapped ions. Scientists could adapt conventional error-correction techniques to the quantum world by using multiple ions to encode each qubit. Here the redundant encoding of information allows the system to tolerate errors, as long as they occur at a sufficiently low rate. In the end, a useful trapped-ion quantum computer would most likely entail the storage and manipulation of at least thousands of ions, trapped in complex arrays of electrodes on microscopic chips.

The first requirement for making a "universal" quantum computer—one that can perform all possible computations—is reliable memory. If we put a qubit in a superposition state of 0 and 1, with the ion's magnetic orientation pointing up and down at the same time, it must remain in that state until the data are processed or measured. Researchers have long known that ions held in electromagnetic traps can act as very good qubit memory registers, with superposition lifetimes (also known as coherence times) exceeding 10 minutes. These relatively long lifetimes result from the extremely weak interaction between an ion and its surroundings.

The second essential ingredient for quantum computing is the ability to manipulate a single qubit. If the qubits are based on the magnetic orientation of a trapped ion, researchers can use oscillating magnetic fields, applied for a specified duration, to flip a qubit (changing it from 0 to 1, and vice versa) or to put it in a superposition state. Given the small distances between the trapped ions—typically a few millionths of a meter—it is difficult to localize the oscillating fields to an individual ion, which is important because we will often want to change one qubit's orientation without changing that of its neighbors. We can solve this problem, however, by using laser beams that are focused on the particular qubit (or qubits) of interest.

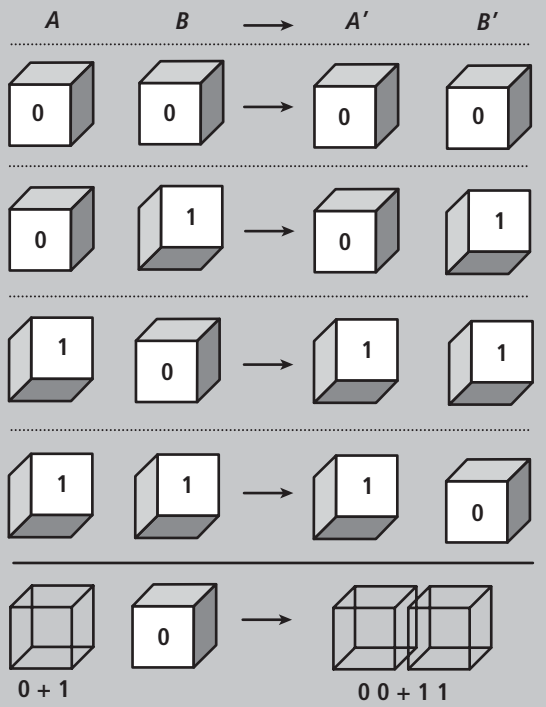
The third basic requirement is the ability to devise at least one type of logic gate between qubits. It can take the same form as classical logic gates—the AND and OR gates that are the building blocks of conventional processors—but it must also act on the superposition states unique to qubits. A popular choice for a two-qubit logic gate is called a controlled not (CNOT) gate. Let us call the qubit inputs *A* and *B*. *A* is the control bit. If the value of *A* is 0, the CNOT gate leaves *B* unchanged; if *A* is 1, the gate flips *B*, changing its value from 0 to 1, and vice versa [*see box above*]. This gate is also called a conditional logic gate, because the action taken on qubit input *B* (whether the bit is flipped or not) depends on the condition of qubit input *A*.

To make a conditional logic gate between two ion qubits, we require a coupling between them—in other words, we need them to talk to each other. Because both qubits are positively charged, their motion is strongly coupled electrically through a phenomenon known as mutual coulomb repulsion. In 1995 Juan Ignacio Cirac and Peter Zoller, both then at the University of Innsbruck in Austria, proposed a way to use this coulomb interaction to couple indirectly

[BASICS]

TRUTH TABLE

A trapped-ion computer would rely on logic gates such as the controlled not (CNOT) gate, which consists of two ions, *A* and *B*. This truth table shows that if *A* (the control bit) has a value of 0, the gate leaves *B* unchanged. But if *A* is 1, the gate flips *B*, changing its value from 0 to 1, and vice versa. And if *A* is in a superposition state (0 and 1 at the same time), the gate puts the two ions in an entangled superposition. (Their state is now identical to the one shown in the box on the bottom of the opposite page.)



POWERS OF TWO

The enormous potential of trapped-ion computers lies in the fact that a system with *N* ions can hold 2^N numbers simultaneously. And as *N* increases, the value of 2^N rises exponentially.

$2^5 = 32$

$2^{10} = 1{,}024$

$2^{50} =$ 1,125,899,906,842,624

$2^{100} =$ 1,267,650,600,228,229, 401,496,703,205,376

JEN CHRISTIANSEN

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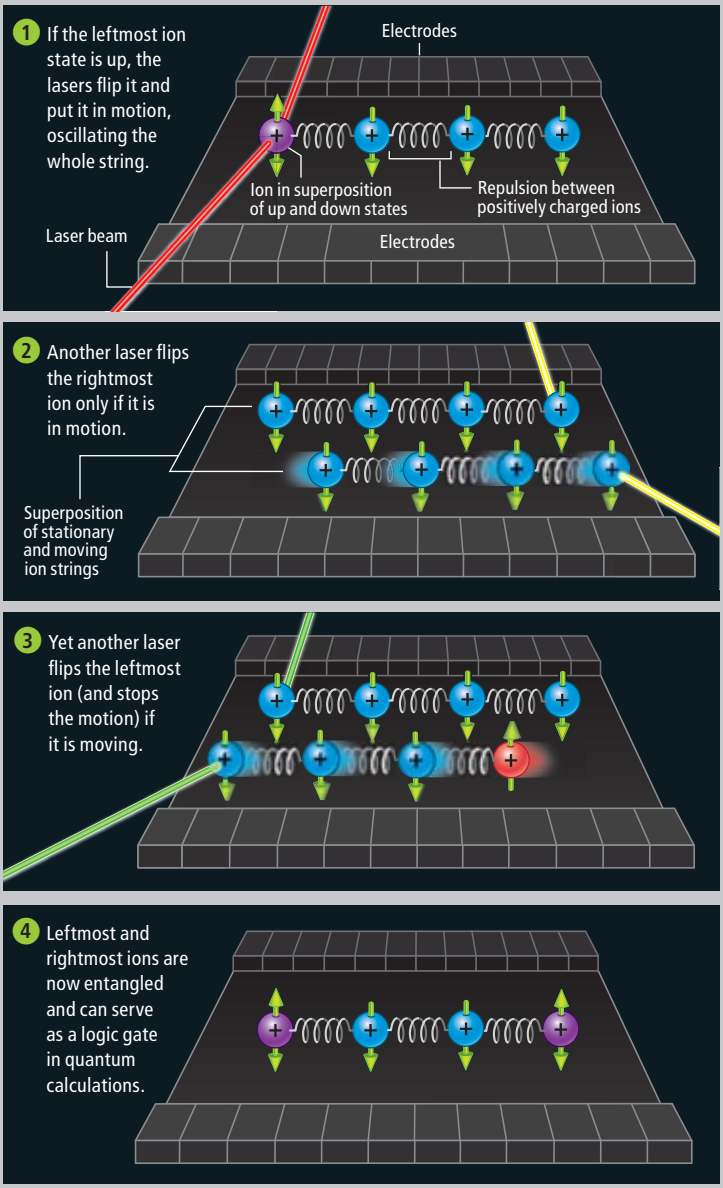
the internal states of the two ion qubits and realize a CNOT gate. A brief explanation of a variant on their gate goes as follows.

First, think about two marbles in a bowl. Assume that the marbles are charged and repel each other. Both marbles want to settle at the bottom of the bowl, but the coulomb repulsion causes them to come to rest on opposite sides, each a bit up the slope. In this state, the marbles would tend to move in tandem: they could, for instance, oscillate back and forth in the bowl along their direction of alignment while preserving the separation distance between them. A pair of qubits in an ion trap would also experience

[ONE APPROACH]

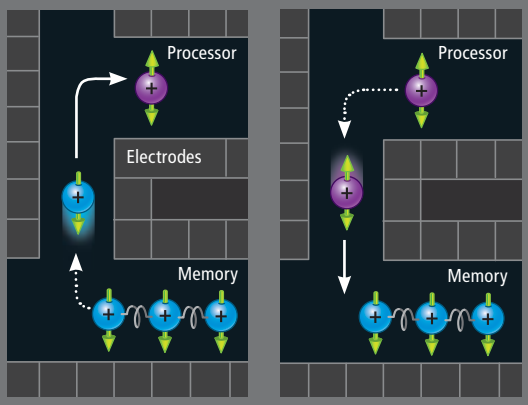
ION STRINGS

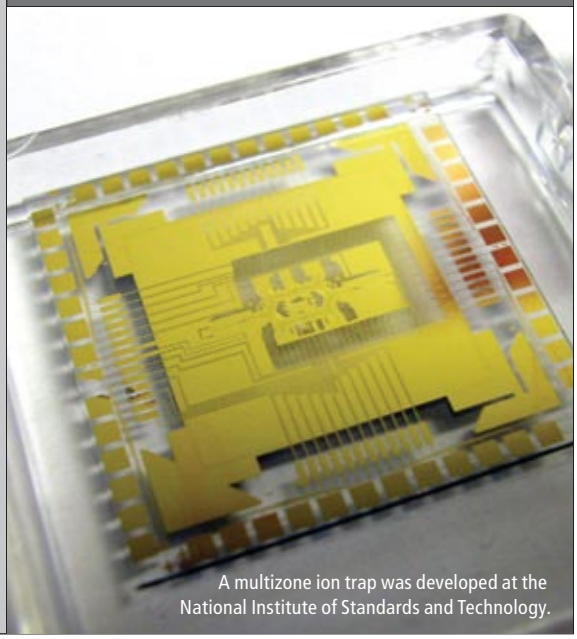
One method for building a trapped-ion computer is to connect the ions through their common motions. A string of ions is electrically levitated between two arrays of electrodes. Because the positively charged particles repel one another, any oscillatory motions imparted to one ion (say, by a laser) will move the whole string. Lasers can also flip the ions' magnetic orientations, which encode the data carried by the string—an up orientation can correspond to 1, and down can represent 0.



THE FUTURE

Scaling this system up to larger numbers of ions presents difficulties, however. It appears that longer strings—those containing more than about 20 ions—would be nearly impossible to control because their many collective modes of common motion would interfere with one another. So scientists have begun to develop gridlike traps in which ions can be moved from a string in the system's memory, say, to another string where data are being processed. The quantum entanglement of the ions allows data to be transferred from one zone of the trap to another.





A multizone ion trap was developed at the National Institute of Standards and Technology.

JEN CHRISTIANSEN (*illustrations*); JASON AMINI *NIST* (*ion trap*)

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this common motion, jiggling back and forth like two pendulum weights connected by a spring. Researchers can excite the common motion by applying photon pressure from a laser beam modulated at the natural oscillation frequency of the trap [*see box on opposite page*].

More important, the laser beam can be made to affect the ion only if its magnetic orientation is up, which here corresponds to a qubit value of 1. What is more, these microscopic bar magnets rotate their orientation while they are oscillating in space, and the amount of rotation depends on whether one or both of the ions are in the 1 state. The net result is that if we apply a specific laser force to the ions for a carefully adjusted duration, we can create a CNOT gate. When the qubits are initialized in superposition states, the action of this gate entangles the ions, making it a fundamental operation for the construction of an arbitrary quantum computation among many ions.

Researchers at several laboratories—including groups at the University of Innsbruck, the University of Michigan at Ann Arbor, the National Institute of Standards and Technology (NIST) and the University of Oxford—have demonstrated working CNOT gates. Of course, none of the gates works perfectly, because they are limited by such things as laser-intensity fluctuations and noisy ambient electric fields, which compromise the integrity of the ions' laser-excited motions. Currently researchers can make a two-qubit gate that operates with a "fidelity" of slightly above 99 percent, meaning that the probability of the gate operating in error is less than 1 percent. But a useful quantum computer may need to achieve a fidelity of about 99.99 percent for error-correction techniques to work properly. One of the main tasks of all trapped-ion research groups is to reduce the background noise enough to reach these goals, and although this effort will be daunting, nothing fundamental stands in the way of its achievement.

Ion Highways

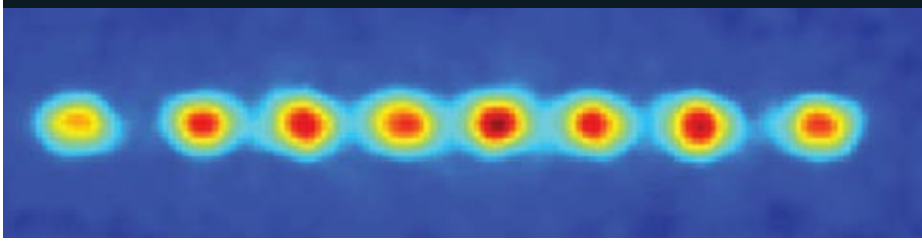
But can researchers really make a full-fledged quantum computer out of trapped ions? Unfortunately, it appears that longer strings of ions—those containing more than about 20 qubits—would be nearly impossible to control because their many collective modes of common motion would interfere with one another. So scientists have begun to explore the idea of dividing the quantum hardware into manageable chunks, performing calculations with short chains of ions that could be shuttled from place to place on the quantum computer chip. Electric forces can move the ion strings without disturbing their internal states, hence preserving the data they carry. And researchers could entangle one string with another to transfer data and perform processing tasks that require the action of many logic gates. The resulting architecture would somewhat resemble the familiar charge-coupled device (CCD) used in digital cameras; just as a CCD can move electric charge across an array of capacitors, a quantum chip could propel strings of individual ions through a grid of linear traps.

Quantum information science offers an opportunity to radically change computing. Scientists may finally realize their dream of creating a quantum machine that can tackle tasks once thought impossible.

Many of the trapped-ion experiments at NIST have involved shuttling ions through a multizone linear trap. Extending this idea to much larger systems, however, will require more sophisticated structures with a multitude of electrodes that could guide the ions in any direction. The electrodes would have to be very small—in the range of 10 to 100 millionths of a meter—to confine and control the ion-shuttling procedure precisely. Fortunately, the builders of trapped-ion quantum computers can take advantage of microfabrication techniques, such as microelectromechanical systems (MEMS) and semiconductor lithography, that are already used to construct conventional computer chips.

Over the past year several research groups have demonstrated the first integrated ion traps. Scientists at the University of Michigan and the Laboratory for Physical Sciences at the University of Maryland employed a gallium arsenide semiconductor structure for their quantum chip. Investigators at NIST developed a new ion-trap geometry in which the ions float above a chip's surface. Groups at Alcatel-Lucent and Sandia National Laboratories have fabricated even fancier ion traps on silicon chips. Much work remains to be done on these chip traps. The atomic noise emanating from nearby surfaces must be reduced, perhaps by cooling the electrodes with liquid nitrogen or liquid helium. And researchers must skillfully choreograph the movement of ions across the chip to avoid heating the particles and

LEVITATED STRING of eight calcium ions are confined in a vacuum chamber and laser-cooled to be nearly at rest. Such a string can perform quantum calculations.



COURTESY OF RAINER BLATT *University of Innsbruck*

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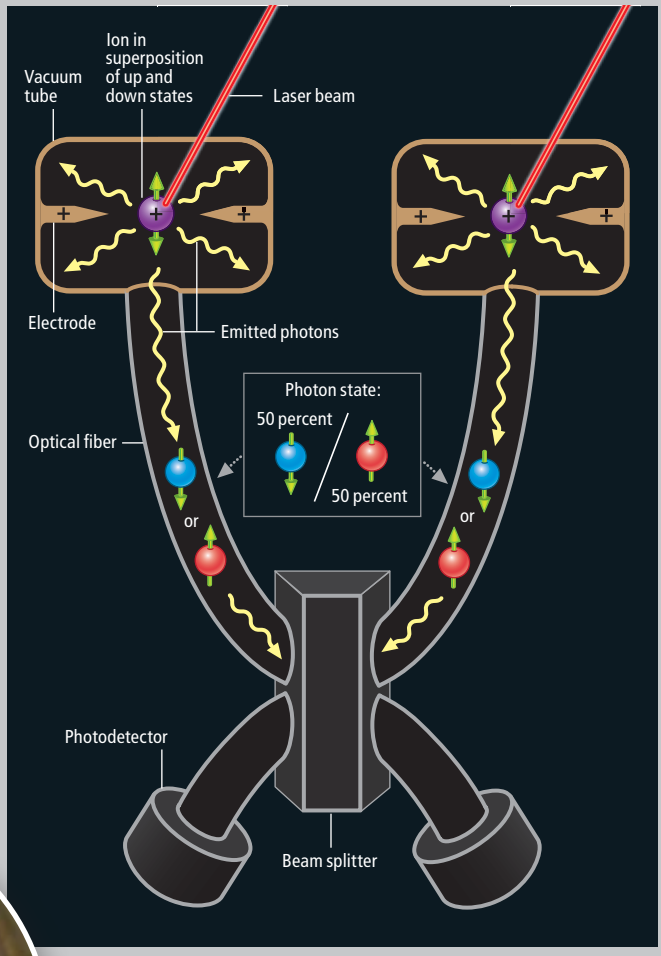
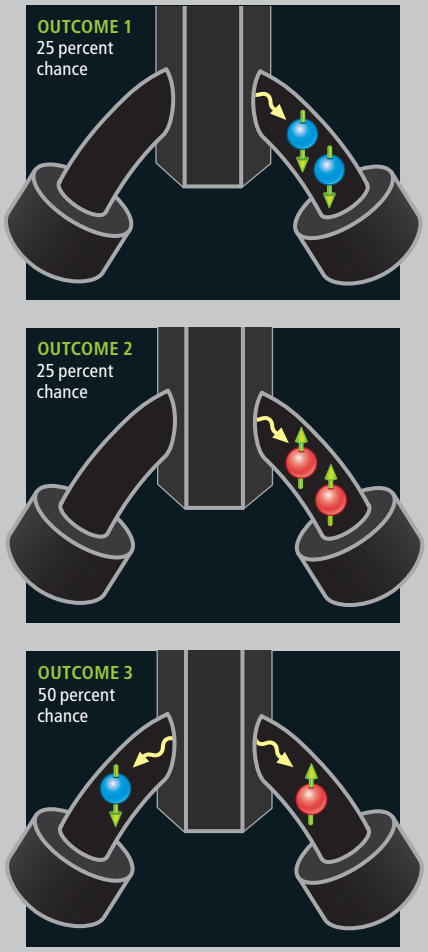
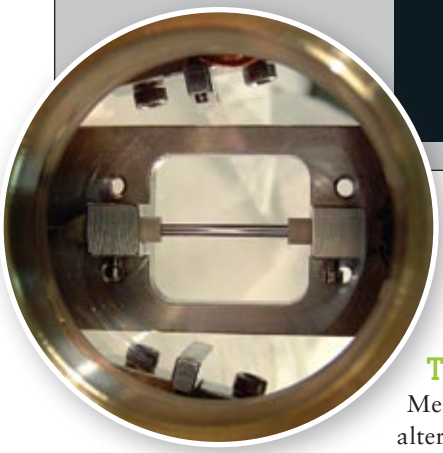
[ANOTHER METHOD]

LINKING IONS WITH PHOTONS

An alternative approach to trapped-ion computing is to link the ions using the photons they emit. Two remotely located trapped ions (*purple*), each isolated in a vacuum tube (*photograph below*), are excited with laser pulses and emit photons into optical fibers. The frequencies of the photons depend on the magnetic orientation of the ions; a photon emitted by an ion in a 50–50 superposition state—half up, half down—would be in a superposition of frequencies (half red and half blue in this example). If the photons from the two ions are in the same state, the beam splitter will shunt both to one photodetector. But if the photons are in different states, they will travel to separate detectors. Once that happens, the ions are entangled, because researchers cannot tell which ion has emitted which photon.







disturbing their positions. For example, the shuttling of ions around a simple corner in a T junction requires the careful synchronization of electric forces.

The Photon Connection

Meanwhile other scientists are pursuing an alternative way to build quantum computers from trapped ions, and this approach may circumvent some of the difficulties in controlling the motion of the ions. Instead of coupling the ions through their oscillatory motions, these researchers are using photons to link the qubits. In a scheme based on ideas described in 2001 by Cirac, Zoller and their colleagues Luming Duan of the University of Michigan and Mikhail Lukin of Harvard University, photons are emitted from each trapped ion so that the attributes of the photons—such as polarization or color—become entangled with the internal, magnetic qubit states of the ion emitter. The photons then travel down optical fibers to a beam splitter, a device typically used to split a light beam in two. In this setup, however, the beam splitter works in reverse: the photons approach the device from opposite sides, and if the particles have the same polarization and color, they interfere with each other and can emerge only along the same path. But if the photons have different polarizations or colors—indicating that the trapped ions are in different qubit states—the particles can follow separate paths to a pair of detectors [*see box above*]. The important point here is that after the photons are detected, it is not possible to tell which ion has emitted which photon, and this quantum phenomenon produces entanglement between the ions.

The emitted photons, though, are not successfully collected or detected in every attempt. In fact, the vast majority of the time the photons are lost and the ions are not entangled. But it is still possible to recover from this type of error

JEN CHRISTIANSEN (*illustrations*); STEVEN OLMSCHENK *Joint Quantum Institute and University of Maryland (ion trap)*

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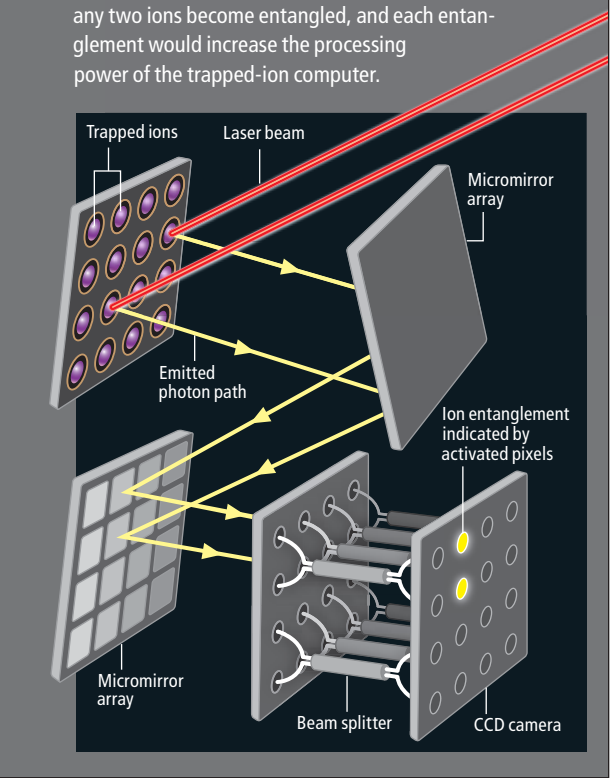
THE FUTURE

Researchers are excited about the photon-linking approach because it offers a relatively easy way to connect large numbers of ions. Laser beams could be directed at an array of trapped ions, and the emitted photons could travel to a bank of beam splitters. A charge-coupled device (CCD) camera could easily detect when any two ions become entangled, and each entanglement would increase the processing power of the trapped-ion computer.



by repeating the process and simply waiting for photons to be simultaneously counted on the detectors. Once this occurs, even though the ions may be widely separated, the manipulation of one of the qubits will affect the other, allowing the construction of a CNOT logic gate.

Scientists at the University of Michigan and the University of Maryland have successfully entangled two trapped-ion qubits, separated by about one meter, using the interference of their emitted photons. The main obstacle in such experiments is the low rate of entanglement generation; the likelihood of capturing these single photons into a fiber is so small that ions are entangled only a few times per minute. That rate could be increased dramatically by surrounding each ion with highly reflective mirrors in a so-called optical cavity, which would greatly improve the coupling of the ion emission with the optical fibers, but this enhancement is currently very difficult to accomplish experimentally. Nevertheless, as long as the interference eventually occurs, researchers can still use the system for quantum information processing. (The procedure is comparable to getting cable TV installed in a new house: although it may take many phone calls to get the service provider to install the system, eventually the cable is hooked up, and you can watch TV.)

Furthermore, investigators can expand the quantum gate operations to large numbers of qubits by connecting additional ion emitters by optical fiber and repeating the procedure until more entangled links are established. It should also be possible to use both photon coupling and the motional coupling discussed earlier to connect several small clusters of trapped ions over remote or even global distances. This is exactly the idea behind a "quantum repeater," in which small quantum computers are networked at periodic distances to maintain a qubit as it travels over hundreds of kilometers. Without such a system the data would usually be lost forever.

The Quantum Future

Scientists are still far from constructing a quantum computer that can take on the daunting challenges—such as factoring very large numbers—that have stymied conventional machines. Still, some features of quantum information processing are already finding uses in the real world. For example, several of the simple logic operations required for two-qubit gates can be employed in atomic clocks, which keep time based on the frequency of the radiation emitted when atoms transition between quantum states. And researchers can apply the techniques for entangling trapped ions to increase the sensitivity of measurements in spectroscopy, the analysis of the light emitted by excited atoms.

The field of quantum information science promises to radically change the rules of computing. Collections of trapped ions are at the forefront of this effort because they offer a level of isolation from the environment that is currently unmatched in most other physical systems. At the same time, through the use of lasers, researchers can readily prepare and measure entangled quantum superpositions devised with small numbers of ions. In the coming years, we look forward to a new generation of trapped-ion chips that may pave the way for quantum computers with much larger numbers of qubits. Then scientists may finally realize their dream of creating a quantum machine that can tackle Herculean tasks once thought to be impossible. ■

THE SMALL FRONTIER

Building a computer with single atoms as the memory elements is, in a sense, a natural limit of computer miniaturization. But as physicist Richard Feynman stated in his 1959 lecture entitled "There's Plenty of Room at the Bottom":

When we get to the very, very small world—say circuits of seven atoms—we have a lot of new things that would happen that represent completely new opportunities for design. Atoms on a small scale behave like* nothing *on a large scale, for they satisfy the laws of quantum mechanics.

MORE TO EXPLORE

Quantum Information Processing with Atoms and Photons. Christopher R. Monroe in *Nature,* Vol. 416, No. 6877, pages 238–246; March 14, 2002.

Rules for a Complex Quantum World. Michael A. Nielsen in *Scientific American,* Vol. 287, No. 5, pages 66–75; November 2002.

The Limits of Quantum Computers. Scott Aaronson in *Scientific American,* Vol. 298, No. 3, pages 62–69; March 2008.

More information about trapped-ion computing is available at **tf.nist.gov/timefreq/ion, www.jqi.umd.edu** and **www.iontrap.umd.edu**

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China's Children of Smoke

Epidemiologists find molecular clues to air pollution's impact on youngsters

By Dan Fagin

KEY CONCEPTS

- A central goal of molecular epidemiology is to tie environmental factors to genetic changes that contribute to disease.
- Some biologists have questioned the approach, because few candidate molecular markers of susceptibility, exposure or early disease have yet been proved to foretell future illness.
- Now researchers may have found the best test case yet for environmental molecular epidemiology: a city in China whose coal-fired power plant was shut down in 2004.
- Preliminary analysis shows that children born in 2002, when the plant was still operating, have smaller heads and lower scores on developmental tests than those born a year after the plant closed. They also have correspondingly higher levels of pollution-related genetic abnormalities.

—The Editors

A few heaping piles of scrap metal and a rusty coal shed are all that is left of the power plant that until recently squatted like an immense, smoke-belching dragon in the middle of Tongliang, a gray city of 100,000 in south-central China. As we walk toward the shed, a Belgian Shepherd begins barking furiously, jerking its iron chain and baring sharp teeth. A brown-eyed face peeks out from the open doorway—it belongs to a girl in a stained shirt, holding a tabby cat that jumps away to hide under a slab of concrete as we approach. The girl is no more than six or seven years old and appears to be living in the shed with her father, who watches us warily from within.

The delegation of local officials who are taking us on a tour of the site are embarrassed; they want to hustle us along to a nearby office to show us an elaborate scale model of an extravagant (by Tongliang standards) 900-unit housing development planned for the property. But Frederica Perera is intrigued. She strides toward the girl and gives a friendly "*ni hao*" and a smile. The girl smiles back before retreating back into the shadows with her father.

Children, after all, are why Perera is here. She is looking for connections between air pollution and disease, especially in children who were exposed to pollutants in the womb. The director of Columbia University's Center for Children's Environmental Health, Perera helped to pioneer the field of molecular epidemiology, which applies the tools of molecular analysis to identify genetic and environmental factors that contribute to disease. She and other molecular epidemiologists who focus on environmental links to illness increasingly do much of their work in the developing world, where pollution is so ubiquitous that its complex connections to health can be calibrated even in small study populations. But their conclusions should also apply in places such as the U.S., Europe and Japan, where environmental exposures are subtler and their effects more difficult to measure in small-scale studies.

Wherever they work, what distinguishes the approach of molecular epidemiologists is their search for biological indicators that closely correlate with toxic exposures and illness. Often these markers take the form of chemicals bound to DNA or of changes in gene structure or activ-

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ILL WIND: A young boy wears a mask against pollution in Linfen, China. Preliminary results from a study conducted in Tongliang, China, reveal that children exposed to highly polluted air while in the womb had more changes in their DNA—and a higher risk of developmental problems—than did those whose mothers breathed cleaner air during pregnancy.

PETER PARKS AFP/Getty Images

ity that match up with particular types of contaminants and disease. Now that DNA microarrays and other screening technologies are making it much easier to measure many of those biomarkers, routine use of such tools could, at least theoretically, save lives by identifying populations at risk from specific pollutants.

The science is still controversial, however, because relatively few candidate molecular biomarkers of susceptibility, exposure or early disease have been fully validated—that is, proved to herald future illness—and because it is very difficult to factor out confounding variables such as diet and genetic predisposition that may be at least as important as exposure to pollutants in causing various ailments. What has proved even more difficult is getting a handle on how those disparate risks may be interacting to affect health.

As a result, more than 25 years after Perera's first paper on the topic, molecular epidemiology has progressed more slowly than its architects had initially hoped, and the consensus among researchers is that no matter how enticing it sounds in theory, real-world complexities have limited its usefulness. Initial enthusiasm for the idea that changes in a few specific biomarkers—the tumor-suppressing protein p53 is a prominent example—could be reliable indicators of early illness has faded as researchers have identified much more complicated etiologies, involving cascades of biochemical changes, for many diseases. "You could say that the reception was a little overenthusiastic early on. There have been some premature claims," Perera acknowledges. "The promise of using biomarkers for early detection and custom-managed treatment has turned out to be not so easy."

But now, in Tongliang, Perera believes she has found the best test case yet for environmental epidemiology at the molecular level—and she and her Columbia colleague, Deliang Tang, are getting results to back up her optimism. How they made their discoveries is almost as interesting as what they found.

A "Biological Dosimeter"

Ever since she began studying biomarkers in 1979, the ones that have interested Perera the most are PAH-DNA adducts, which she and Tang are now measuring in the white blood cells of children who were exposed to exhausts from the Tongliang power plant. PAHs, or polycyclic aromatic hydrocarbons, are a large family of compounds formed by the incomplete combustion of organic material—especially coal, but also other fossil fuels, cigarettes and even barbecued meat. They are among the most widespread and harmful air pollutants in the world. What interests Perera most about PAHs is their sticky

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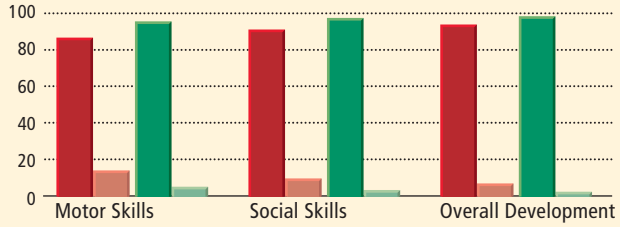
[FINDINGS]

DEVELOPMENTAL DELAYS

Tongliang children born in 2002, when the local coal-burning power plant was still open, scored worse on tests of motor and social skills than did their counterparts born in 2005, one year after the plant stopped operating. Researchers classified children as developmentally delayed if they scored below 85 on a standard assessment known as the Gesell test. The children born in 2002 had higher concentrations in their white blood cells of PAH-DNA adducts—DNA alterations caused by exposures to harmful chemicals, called polycyclic aromatic hydrocarbons (PAHs) in polluted air. Among children born in 2002, adduct frequency closely correlated with developmental delay.

HOW CHILDREN BORN IN 2002 DIFFERED FROM THOSE BORN IN 2005

Percentage of subjects who were normal vs. delayed



CHILDREN BORN IN 2002 (110 subjects) Normal Delayed

CHILDREN BORN IN 2005 (107 subjects) Normal Delayed

Children in cities where the air was cleaner had fewer adducts and were less likely to suffer from growth deficits.

molecular structure. Many PAHs readily form tight, covalent bonds with DNA. Those fused pollutant-DNA complexes, or adducts, can disrupt replication of the genome during cell division, altering the functions of genes that promote or suppress disease.

The coal-burning power station that loomed over Tongliang was a Vesuvius of PAHs, and its closure in 2004 changed environmental conditions in the city virtually overnight. That makes Tongliang something very rare in the world of epidemiology: a feasible laboratory for measuring the before-and-after health impacts of air pollutants. The city is still far from pristine, but passing cars no longer kick up clouds of black soot from the street and families can hang their wash outside to dry for more than a few minutes without their white shirts turning gray. The air-pollution monitors that the Columbia team installed around Tongliang confirm the improvements: airborne concentrations of one of the most important PAHs, benzo(a)pyrene, or BaP, fell by about 30 percent between 2002 and 2005. Other PAHs declined even more.

The changes that interest Perera the most, however, are taking place in the bodies of the city's youngest residents. Since 2002 she and Tang, along with Tin-yu Li of Chongqing Children's Hospital, have been studying 450 children who live within two kilometers of the plant site by testing their DNA and measuring their physical and mental development starting at birth. The researchers' preliminary analysis shows that children born in 2002, when the power plant was still operating, have smaller heads and score worse on developmental tests than those born in 2005, a year after the plant closed. There are also differences at the molecular level: concentrations of BaP-DNA adducts were about 40 percent higher in the white blood cells of newborn babies in Tongliang in 2002 than in those of children born three years later.

Perhaps most meaningful of all, in the children born in 2002, measured concentrations of BaP-DNA adducts closely correlated with head circumference and developmental test scores. In other words, the more damage a child's DNA suffered in the womb, the more likely he or she was to be born with a smaller head and to score worse on tests of motor skills and overall development as a toddler. The correlations were weaker among babies born in 2005, suggesting that air pollution becomes less of a risk as overall levels drop. Children born in 2005 will probably be slightly less likely to get cancer, according to Perera, whose previous work suggests that adduct counts correlate with cancer risk.

The Tongliang data, along with the results of earlier studies she conducted in Poland and New York City, suggest that measurements of adducts in white blood cells are reliable "biological dosimeters" for estimating the impact of PAHs

MELISSA THOMAS (*graph*); DAN FAGIN (*child taking test*)

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on neurodevelopment, Perera says. That being the case, testing for adducts could someday become part of a pediatrician's arsenal for identifying children who are at high risk for developmental problems and thus need early intervention, she observes.

The 2002/2005 comparison is "a very powerful finding," remarks molecular epidemiologist John D. Groopman of Johns Hopkins University. "One of the critical steps in the validation of biomarkers is to demonstrate that if you modulate the biomarker, you can show an effect on a health outcome."

"I'm in awe of what Dr. Perera has accomplished," adds John F. Rosen of Children's Hospital at Montefiore in Bronx, N.Y., a longtime lead-poisoning researcher who has also worked in China. "Translating her clinical results unquestionably will advance child health in China and the rest of the world."

Finding Tongliang

A fine mist was falling the morning I arrived in Tongliang with Perera and Tang. The hills surrounding the city on three sides seemed as blurred as they must have looked back in the days when the coal plant was running. Most of the electricity in this part of China comes from hydropower, but because snowmelt does not swell the Yangtze River until the spring, many of the smaller cities have relied on primitive coal-burning plants that lack even basic pollution controls to fill the gap during the winter months. Tongliang's power plant consumed more than 4,000 tons of coal a month between November and May, and that coal was especially problematic because it contained very high concentrations of sulfur and thus did not burn completely. PAH-laden ash and exhaust gases would pour out of the plant's 279-foot smokestack and settle over the low-lying city like a thick blanket.

Back in 2000, Perera had been searching for just such a place to build on her two decades of research into the role of PAH-DNA adducts as indicators of disease risk. Her initial studies—the first ever in human subjects—had measured the adducts in the lung tissue of adult cancer patients [see "Uncovering New Clues to Cancer Risk," by Frederica P. Perera; Scientific American, May 1996], and she went on to measure them in mothers and children living in polluted neighborhoods of New York City and the industrial city of Kraków, Poland. What she found is that people exposed to air pollution had higher adduct levels in their blood and that those high levels in turn correlated with the presence of genetic mutations that were known to be risk factors for cancer and developmental problems in young children. Children in cities where the air was cleaner, Perera determined, had fewer adducts and were less likely to suffer from growth deficits.

Still, her studies were small, and she could not rule out the possibility that unmeasured lifestyle differences, instead of pollution, might explain the differences in health and in adduct levels that she found between mothers and children who lived in polluted cities and those who did not. Now Perera wanted to take the next step by finding one city in which emissions of PAHs were abruptly reduced, allowing a before-and-after comparison in a single, discrete population.

China, with its extreme environmental problems and an authoritarian government capable of shutting down a major polluter in one fell swoop, was the obvious place to look. And Tang was the best person to direct the study Perera envisioned. A physician and Shanghai native, Tang did his doctoral training in public health in Perera's lab and was now her frequent research collaborator. For his study he would have to train a small army of Chinese doctors and nurses to collect placentas and cord blood from mothers enrolled in the study and to administer cognitive tests to the children as they grew. He would also need to parley with an array of government officials, from Beijing bureaucrats to provincial apparatchiks, to secure the cooperation of hospitals, arrange for lab space, import pollution-control equipment and export blood samples—all very politically sensitive tasks.

MOLECULAR EPIDEMIOLOGISTS Frederica P. Perera and Deliang Tang looked at 12 sites in China before deciding to conduct their study of PAH-DNA adducts in Tongliang.

ALISON FRANKEL (*Fagin*); JUSTIN WEINSTEIN (*Perera and Tang*)

[THE AUTHOR]

Dan Fagin is an associate professor of journalism and the director of the Science, Health and Environmental Reporting Program at New York University. He is working on a book about gene-environment interactions and a childhood cancer cluster in Toms River, N.J. This is his second article for *Scientific American.* His first, in the December 2007 issue, examined the risk of adding fluoride to drinking water.

ON THE WEB

For more on China's environmental challenges, go to www.SciAm.com/china

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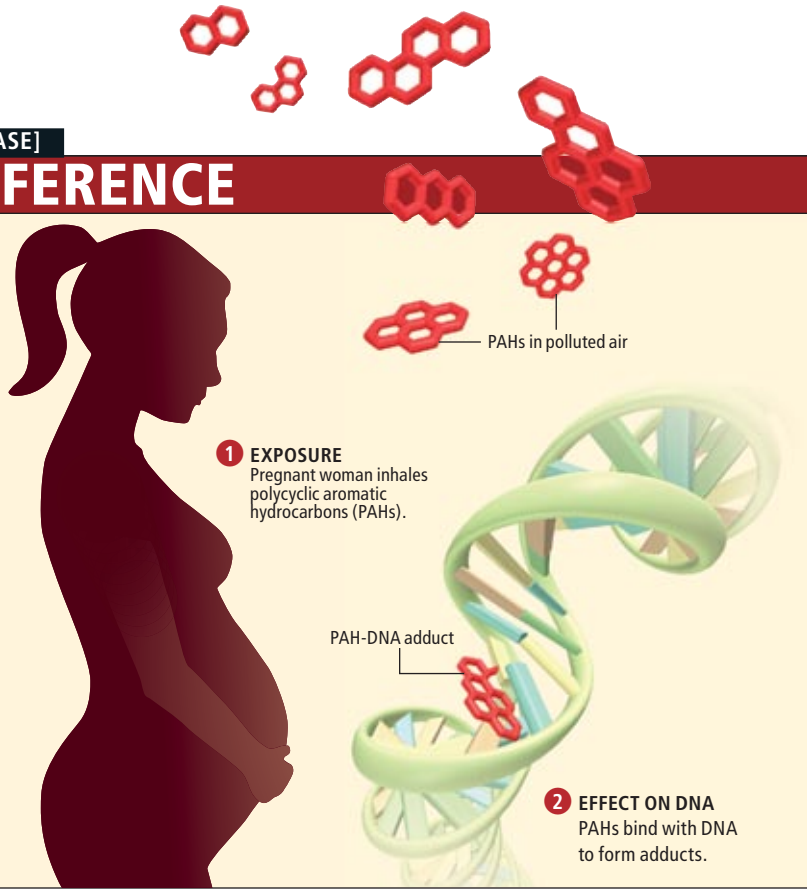
[FROM POLLUTION TO DISEASE]

DNA INTERFERENCE

The findings in China confirm earlier research indicating that PAH-DNA adducts can serve as a fingerprint of exposure to pollution. These adducts may also change the functions of genes that promote or suppress disease, although exactly how they might lead to developmental decrements in fetuses exposed to them is unclear. Several mechanisms have been proposed, however.



"This is not some vague, theoretical threat. We have all the evidence we need to reduce these exposures right now."
—Frederica Perera

Perera and Tang investigated 12 candidate sites before settling on Tongliang, where its sole power plant was scheduled to close as part of a government program to replace inefficient coal-burning plants. Tongliang was a good fit not only because the plant was set to shut down but also because the city had relatively few other important sources of air pollution aside from vehicle traffic. Natural gas had already replaced wood- and coal-burning stoves in the city, which had no large factories. The four local hospitals that agreed to participate were just large enough to collectively generate enough cases to satisfy the statistical requirements of the study Perera and Tang planned: 150 nonsmoking women whose pregnancies coincided with the months the plant operated. Additional mothers and newborns would be tested in later years, after the power plant closed.

But when Perera and Tang arrived in Tongliang in the spring of 2002 to begin recruiting pregnant women for the study, they found themselves in the middle of a controversy. The question of whether to close the power plant had been a simmering issue for years in Tongliang. Some local mothers had even stood outside during government meetings in silent protest against continued operation—an extraordinary step in China. Now city officials, worried about the economic impact, were considering retrofitting the plant or moving it to the edge of the city instead of shuttering it. The Columbia researchers had to wait for months for a resolution. Ultimately, publicity over their planned study helped to tip the balance in favor of closure. The old smokestack spewed its final cloud of gray smoke in May 2004.

Persistent Complications

Three anxious young fathers, all of them smoking cigarettes, slump in the crowded central hallway of Tongliang County Maternal Hospital, not far from two "No Smoking" signs. Smoking is endemic among Chinese men—half of the male population and two thirds of adult men younger than 25 light up regularly—and the nurses and doctors seem to have given up trying to enforce a ban.

In a room at the end of the corridor, medical personnel are lavishing attention on a young boy named Junshan Li, who was born in the spring of 2002, when the power plant was still going strong. Li is one of the original 150 subjects of the Tongliang study, but there are no signs today that he is anything but a healthy, active five-year-old—active enough to have broken his collarbone a week earlier in a playground accident. Li is at the hospital today not because of the collarbone injury but for his yearly developmental assessment for Perera and Tang's study. At the moment, he is perched on the edge of a chair and excitedly shouting out numbers in Chinese—

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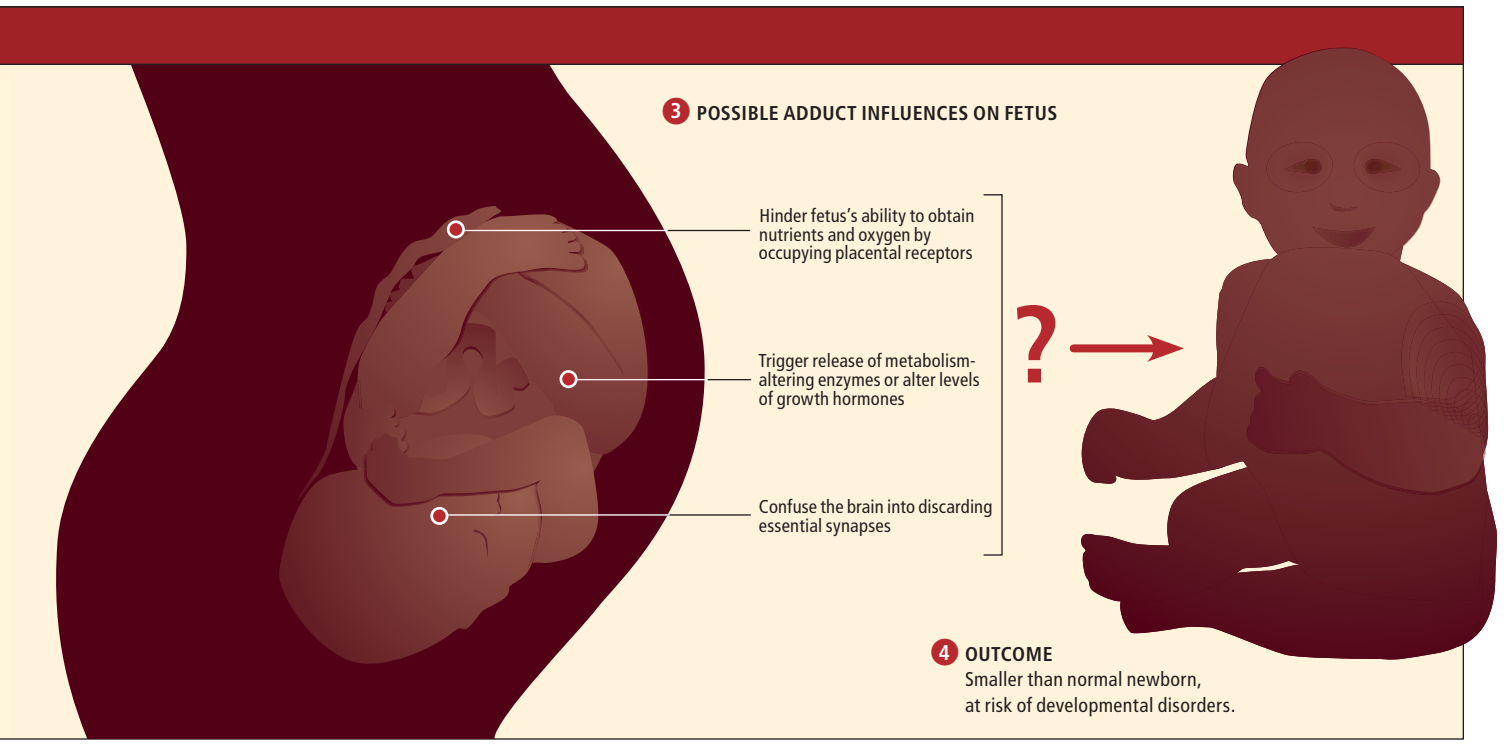

MELISSA THOMAS (*human figures*); KEN EWARD *BioGrafx* (*molecular structures*)

"*ba!*" … "*san!*" … "*qi!*"—in response to simple arithmetic questions posed by a tester, a young pediatrician named Xu Tan. Her goal is to assess Li's growth both mentally and physically; after the test, Tan will weigh him and measure his height and head circumference.

The scene in the hospital illustrates a key challenge of molecular epidemiology. The growth and developmental deficiencies Perera and Tang are scrutinizing for links to prenatal exposure to PAH pollution are subtle and can have multiple causes—including secondhand tobacco smoke such as that emanating from the fathers smoking at the other end of the hallway. The researchers have tried to deal with the problem of alternative causes by enrolling only nonsmoking mothers with low-risk pregnancies and by asking mothers about their education, family smoking habits, and exposure to PAHs via grilled meats and other foods, as well as some other possibly confounding explanations. The investigators have also taken measurements of neurotoxic metals and antioxidants in blood, because those could also affect child development. So they are reasonably confident that the correlations they have uncovered between adduct counts in Tongliang children and several important measures of growth and learning stem mostly from exposure to air pollution.

Though statistically significant, the differences between Tongliang children born in 2002, when the power plant was still open, and those born in 2005, after it had closed, are small: a few millimeters in head circumference and height, an ounce of body weight, a point or two on a developmental test. According to Perera, the results suggest that the 2002 children will be slightly more likely to be slower learners and to need extra help at school and will develop fine-motor skills later on average than their counterparts born in 2005.

These kinds of subtle health effects have always been a source of contention in biomarker research. In the 1970s and 1980s Herbert L. Needleman, now at the University of Pittsburgh, pioneered the study of lead levels across populations by grinding up baby teeth and measuring trace levels of the metal, eventually finding correlations with diminished learning capacity and delinquent behavior. But the indistinct nature of the neurological problems Needleman was seeing, and the very low levels of lead he was measuring, opened his work to fierce criticism from the lead industry. Ultimately, his findings were replicated and are now widely accepted as a key justification for removing lead from gasoline and paint. Moves to crack down on secondhand smoke, similarly, have cited studies that measured blood and urine levels of cotinine, the most important breakdown product of nicotine. Cotinine levels in pregnant mothers and newborns have become extensively used markers in

FAST FACTS

- Coal provides about **70%** of China's energy.
- China is home to **2 of the 10** most polluted places on earth, as evaluated by the Blacksmith Institute: Linfen and Tianying.
- According to the World Health Organization, diseases triggered by air pollution kill an estimated **656,000** Chinese citizens every year—the highest incidence in the world.

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HAZY ORIGINS: Like pollution, smoking, diet and genetic predisposition may be important in bringing about various disorders, making it difficult to discern the specific role of pollution. In the Tongliang study, the team found correlations between adduct counts and delayed development, even after factoring out alternative influences—a good sign that dirty air was involved.

GREG BAKER *AP Photo*

WHAT'S NEXT

- Continue studying the Tongliang children for at least four more years to assess developmental and respiratory health through age 10. Measured biomarkers will include PAH-DNA adducts, epigenetic alterations, lead and mercury.
- Evaluate whether some Tongliang youngsters are at greater risk of illness than others because of interactions between prenatal exposure to pollutants and genetic and nutritional susceptibility factors that vary from child to child.
- Conduct a combined analysis of data from ongoing parallel studies of 1,500 pairs of mothers and children in the U.S., Poland and China. The goal is to gauge the risks of prenatal exposure to air pollution and study exposure-susceptibility interactions in different ethnic groups and across a gradient of exposure.

research into links between environmental tobacco smoke and a broad range of developmental problems in children.

There is an additional complication in drawing conclusions about health effects by measuring molecular biomarkers. Just because concentrations of lead, cotinine or PAH-DNA adducts are relatively easy to measure in the bloodstream does not mean that the same dose is reaching the brain or other organs where meaningful damage can occur. Earlier adduct studies, some of them by Perera, have suggested that white blood cells are a reasonable proxy for target organs such as the brain and lungs, but contaminants are rarely distributed uniformly throughout the body, and metabolic differences can cause huge variations among individuals even if they are part of a cohesive population that breathes the same air or drinks the same water.

Adducts do have one important advantage over blood measurements of lead and cotinine: they are indicators not just that a contaminant is present in the body but that it is having a discernible effect, in this case by altering DNA molecules. Here, too, however, there are some big uncertainties because no consensus exists on how the formation of adducts could lead to developmental problems in children. In cancer research, where Perera did her initial work with adducts, the connection is somewhat clearer because an adduct's ability to disrupt accurate genomic copying during cell division could trigger mutations and other genetic changes that give rise to malignant cells. But for developmental deficits in children, the theories are more nebulous.

One of the leading ideas about how PAHs may affect the brain involves the "neural pruning," or controlled nerve cell death, that occurs naturally as the developing brain adjusts to its environment and becomes more efficient by discarding synapses it does not need. The presence of PAHs may alter brain function by extending this process, called apoptosis, to essential synapses as well—both in the womb and in the child's early life. Another prominent theory is that PAHs disrupt a fetus's ability to obtain nutrients and oxygen by occupying molecular receptor sites in the placenta. The pollutants may also trigger the release of metabolism-altering enzymes in fetuses and young children and may also alter levels of growth-regulating hormones. The likeliest answer, some experts suggest, is that most or perhaps even all these mechanisms are taking a toll on the brains of children exposed to high levels of air pollution.

"One of the things we've come to learn over the past 10 years is how many pathways there are in many common diseases," says Groopman, whose studies in China and elsewhere have focused on the interaction of aflatoxins with human hepatitis B virus in inducing liver cancer. Aflatoxins, which are produced by *Aspergillus* fungi, are a ubiquitous food contaminant in China and Africa. "With aflatoxin and liver cancer, you're dealing with just one compound and with a specific disease that is very common in countries like China. There are no other confounding sources," he points out. PAHs and childhood development, he adds, "are a much more complicated story."

Next Steps

The next steps, Perera and Groopman agree, will be to scale up and drill down. Larger studies with greater statistical power, involving perhaps thousands of children, may be able to find stronger correlations between PAH exposures and specific developmental problems. Meanwhile investigators will also be delving into the intricacies of neural chemistry in the search for new biomarkers that will allow them to better measure the precise changes in the brain that give rise to growth and learning problems.

That search is already taking scientists into the realm of epigenetics, which is the study of

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heritable, environmentally induced changes that alter the functions of genes without changing their underlying sequence of DNA codes, as PAH adducts do. According to Perera, some evidence already exists that PAHs can lead to epigenetic changes in gene activity that cannot be identified by looking for breaks or disruptions in the genetic code itself. Because adducts are not a proxy for those epigenetic changes, Perera and other molecular epidemiologists are starting to turn to other biomarkers, such as DNA methylation, which is the attachment of methyl groups (CH_3) to genetic material. Methylation typically silences genes, and some evidence suggests that methylation increases with PAH exposure and prevents genes from giving rise to proteins involved in suppressing some diseases, including cancer.

If epigenetic changes turn out to be crucial in altering a child's capacity to grow and learn, then counting methyl groups may end up being a better dosimeter for pollution's impact on the brain than counting PAH-DNA adducts. The Tongliang study may help settle that question, because Perera and Tang plan to analyze all their Tongliang blood samples for DNA methylation and perhaps for other epigenetic biomarkers as well.

Someday doctors may be able to test for a battery of biomarkers—both genetic and epigenetic—to assess a child's overall risk for a wide range of health and developmental problems. For now, though, children such as the girl in the abandoned coal shed in Tongliang will have to rely on their governments to protect them from PAHs and other harmful air pollutants, and Perera never misses a chance to prod public officials to do so. "Tongliang is important because it shows that governments can take specific actions to reduce exposures," she asserts. "Instead of just guessing, we can measure the improvements." The ability to measure cause and effect is especially important in China and other fast-growing countries that are making hard choices about whether to continue to rely heavily on coal or move to cleaner but more expensive energy sources.

The complexities and uncertainties of molecular epidemiology, Perera says, should not obscure the overall message of the data she has accumulated during 29 years spent studying the health effects of air pollution in Finland, Poland, China and her own neighborhood near Columbia in upper Manhattan. That message is as relevant in developed nations as it is in heavily polluted China, she explains, because PAHs are a ubiquitous pollutant capable of affecting children even at relatively low concentrations. In New York City, where airborne PAH levels are more than 10 times lower than in Tongliang, "we have been able to measure the effects in reduced fetal growth and neurodevelopmental impacts," Perera notes. "This is not some vague, theoretical threat that may or may not turn out to be valid with more study. We have all the evidence we need to reduce these exposures right now."

Even as Perera and Tang continue to analyze their Tongliang data, they are on the prowl for opportunities to launch a much larger study based on the same before-and-after premise as the work in Tongliang. "It would require the magic of finding just the right kind of place, in just the right setting," she says. "We've got our eyes peeled for that." ■

MORE TO EXPLORE

Molecular Epidemiology: On the Path to Prevention? Frederica P. Perera in *Journal of the National Cancer Institute,* Vol. 92, No. 8, pages 602–612; April 19, 2000.

Effect of Prenatal Exposure to Airborne Polycyclic Aromatic Hydrocarbons on Neurodevelopment in the First 3 Years of Life Among Inner-City Children. Frederica P. Perera, Virginia Rauh, Robin M. Whyatt, Wei-Yann Tsai, Deliang Tang, Diurka Diaz, Lori Hoepner, Dana Barr, Yi-Hsuan Tu, David Camann and Patrick Kinney in *Environmental Health Perspectives,* Vol. 114, No. 8, pages 1287–1292; August 2006.

Developmental Neurotoxicity of Industrial Chemicals. Philippe Grandjean and Philip J. Landrigan in *Lancet,* Vol. 368, pages 2167–2178; December 16, 2006.

Molecular Epidemiology and Biomarkers in Etiologic Cancer Research: The New in Light of the Old. Paolo Vineis and Frederica Perera in *Cancer Epidemiology Biomarkers & Prevention,* Vol. 16, No. 10, pages 1954–1965; October 2007.

[ANOTHER BIOMARKER]

MUTING GENES

PAHs can affect genes by causing mutations in the DNA code letters. They may also alter gene activity through what are termed epigenetic changes. For example, PAH exposure appears to increase DNA methylation, in which methyl groups (CH_3) attach to DNA. Methylation tends to silence genes and can shut off ones needed to suppress certain diseases, including cancer.

KEN EWARD *BioGrafx*

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BRACING FOR A SOLAR SUPERSTORM

By Sten F. Odenwald and James L. Green

A recurrence of the 1859 solar superstorm would be a cosmic Katrina, causing billions of dollars of damage to satellites, power grids and radio communications

As night was falling across the Americas on Sunday, August 28, 1859, the phantom shapes of the auroras could already be seen overhead. From Maine to the tip of Florida, vivid curtains of light took the skies. Startled Cubans saw the auroras directly overhead; ships' logs near the equator described crimson lights reaching halfway to the zenith. Many people thought their cities had caught fire. Scientific instruments around the world, patiently recording minute changes in Earth's magnetism, suddenly shot off scale, and spurious electric currents surged into the world's telegraph systems. In Baltimore telegraph operators labored from 8 P.M. until 10 A.M. the next day to transmit a mere 400-word press report.

Just before noon the following Thursday, September 1, English astronomer Richard C. Carrington was sketching a curious group of sunspots—curious on account of the dark areas' enormous size. At 11:18 A.M. he witnessed an intense white light flash from two locations within the sunspot group. He called out in vain to anyone in the observatory to come see the brief five-minute spectacle, but solitary astronomers seldom have an audience to share their excitement. Seventeen hours later in the Americas a second wave of auroras turned night to day as far south as Panama. People could read the newspaper by their crimson and green light. Gold miners in the Rocky Mountains woke up and ate breakfast at 1 A.M., thinking the sun had risen on a cloudy day. Telegraph systems became unusable across Europe and North America.

The news media of the day looked for researchers able to explain the phenomena, but at the time scientists scarcely understood auroral displays at all. Were they meteoritic matter from space, reflected light from polar icebergs or a high-altitude version of lightning? It was the Great Aurora of 1859 itself that ushered in a new paradigm. The October 15 issue of *Scientific American* noted that "a connection between the northern lights and forces of electricity and magnetism is now fully established." Work since then has established that auroral displays ultimately originate in violent events on the sun, which fire off huge clouds of plasma and mo-

PAT RAWLINGS SAIC

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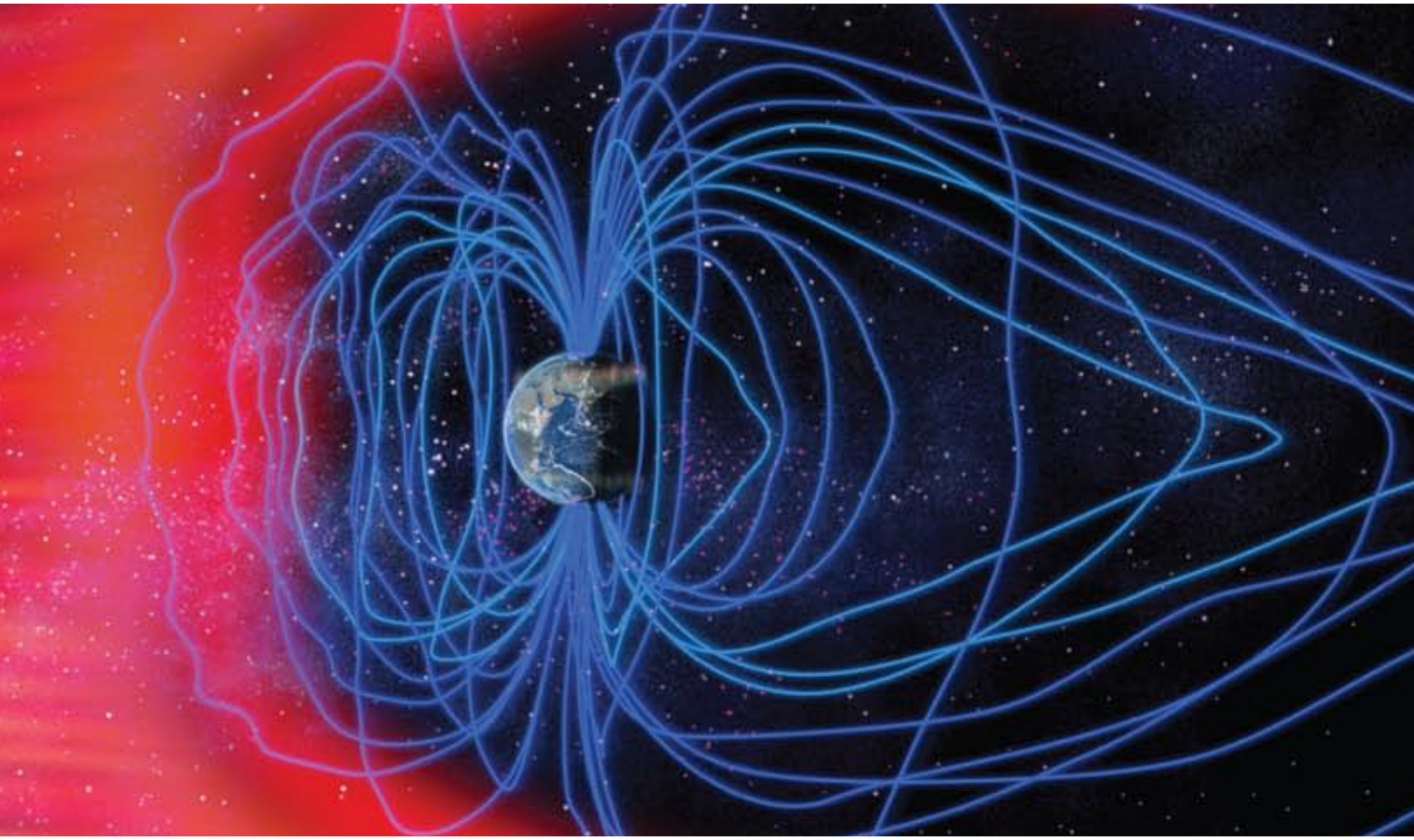

mentarily disrupt our planet's magnetic field.

The impact of the 1859 storm was muted only by the infancy of our technological civilization at that time. Were it to happen today, it could severely damage satellites, disable radio communications and cause continent-wide electrical blackouts that would require weeks or longer to recover from. Although a storm of that magnitude is a comfortably rare once-in-500-years event, those with half its intensity hit every 50 years or so. The last one, which occurred on November 13, 1960, led to worldwide geomagnetic disturbances and radio outages. If we make no preparations, by some calculations the direct and indirect costs of another superstorm could equal that of a major hurricane or earthquake.

The Big One

The number of sunspots, along with other signs of solar magnetic activity, waxes and wanes on an 11-year cycle. The current cycle began this past January; over the coming half a decade, solar activity will ramp up from its current lull. During the previous 11 years, 21,000 flares and 13,000 clouds of ionized gas, or plasma, exploded from the sun's surface. These phenomena, collectively termed solar storms, arise from the relentless churning of solar gases. In some ways, they are scaled-up versions of terrestrial storms, with the important difference that magnetic fields lace the solar gases that sculpt and energize them. Flares are analogous to lightning storms; they are bursts of energetic particles and intense x-rays resulting from changes in the magnetic field on a relatively small scale by the sun's standards, spanning thousands of kilometers. So-called coronal mass ejections (CMEs) are analogous to hurricanes; they are giant magnetic bubbles, millions of kilometers across, that hurl billion-ton plasma clouds into space at several million kilometers per hour.

Most of these storms result in nothing more than auroras dancing in the polar skies—the equivalent of a minor afternoon rainstorm on Earth. Occasionally, however, the sun lets loose a gale. No one living today has ever experienced a full-blown superstorm, but telltale signs of them have turned up in some surprising places.

KEY CONCEPTS

- The solar superstorm of 1859 was the fiercest ever recorded. Auroras filled the sky as far south as the Caribbean, magnetic compasses went haywire and telegraph systems failed.
- Ice cores suggest that such a blast of solar particles happens only once every 500 years, but even the storms every 50 years could fry satellites, jam radios and cause coast-to-coast blackouts.
- The cost of such an event justifies more systematic solar monitoring and beefier protection for satellites and the power grid.

—The Editors

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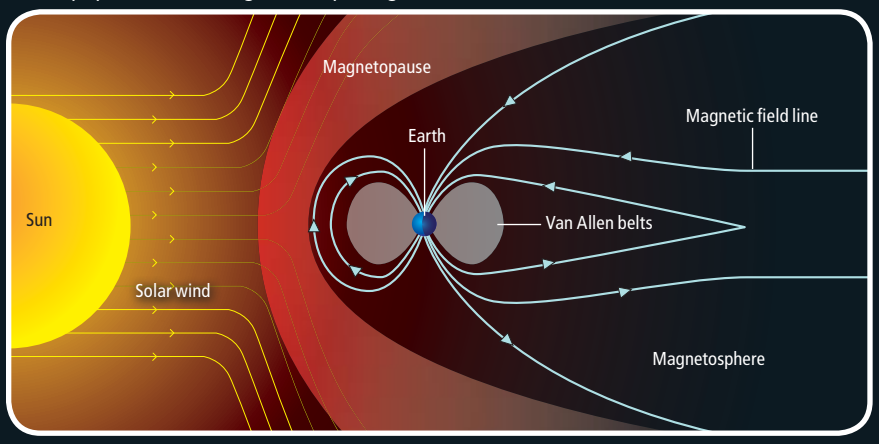
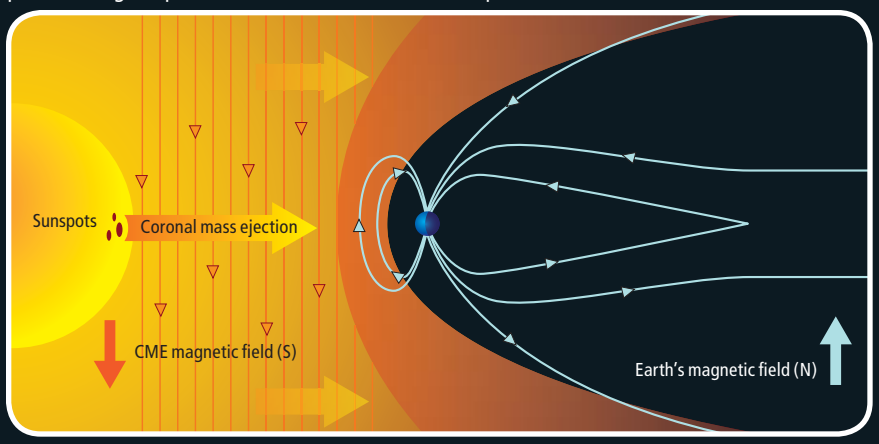
Impact of a Coronal Mass Ejection

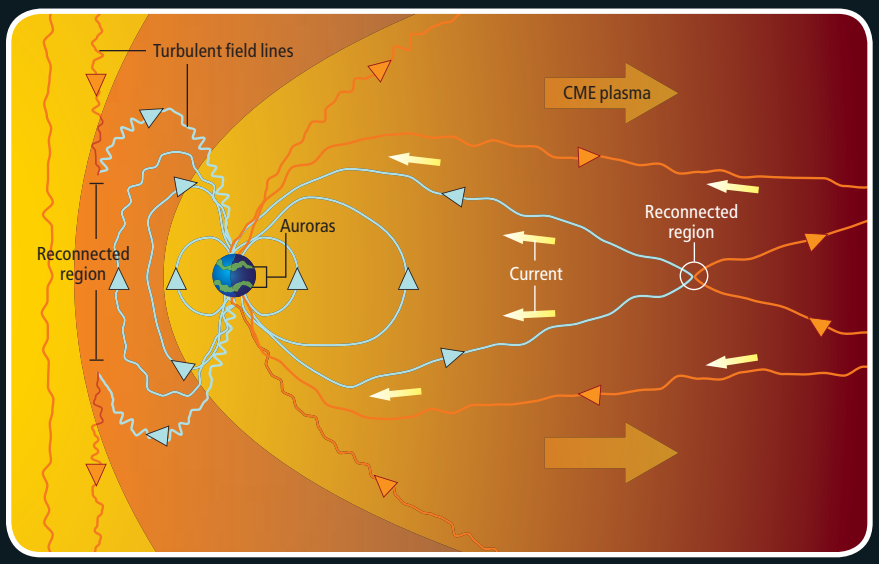
NORMAL CONDITIONS: Earth's magnetic field typically deflects the charged particles streaming out from the sun, carving out a teardrop-shaped volume known as the magnetosphere. On the sun-facing side, the boundary, or magnetopause, is about 60,000 kilometers from our planet. The field also traps particles in a doughnut-shaped region known as the Van Allen belts.



FIRST STAGES OF IMPACT: When the sun fires off a coronal mass ejection (CME), this bubble of ionized gas greatly compresses the magnetosphere. In extreme cases such as superstorms, it can push the magnetopause into the Van Allen belts and wipe them out.



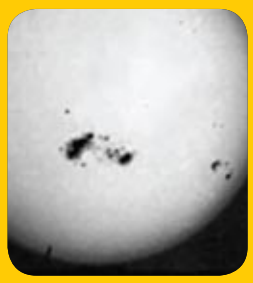
MAGNETIC RECONNECTION: The solar gas has its own magnetic field, and as it streams past our planet, it stirs up turbulence in Earth's magnetic field. If this field points in the opposite direction as Earth's, the two can link up, or reconnect—releasing magnetic energy that accelerates particles and thereby creates bright auroras and powerful electric currents.



The 1859 Superstorm

The authors have reconstructed what happened in 1859, based in part on similar (though less intense) events seen by modern satellites. UTC is Coordinated Universal Time—basically, Greenwich Mean Time.

August 26
Large sunspot group appears near longitude 55 degrees west on the sun; first CME possibly launched.


SUNSPOTS

August 28
CME arrives at Earth with a glancing blow because of the solar longitude of its source; its magnetic orientation is northward.

August 28 07:30 UTC
Greenwich Magnetic Observatory detects a disturbance, signaling compression of the magnetosphere.

CORONAL MASS EJECTION

August 28 22:55 UTC
Main storm phase begins, with large magnetic disturbances, telegraphic disruptions and auroral sightings as far south as magnetic latitude 25 degrees north.

AURORA SIGHTINGS

August 30
Geomagnetic disturbances from first CME end.

September 1 11:15 UTC
Astronomer Richard C. Carrington, among others, sights a white-light flare on the sun; the large sunspot group has rotated to longitude 12 degrees west.

X-RAY FLARE

September 2 05:00 UTC
Greenwich and Kew magnetic observatories detect disturbances followed immediately by geomagnetic chaos; second CME arrives at Earth within 17.5 hours, traveling at 2,380 kilometers per second with southward magnetic orientation; auroras appear down to magnetic latitude 18 degrees north.

AURORA SIGHTINGS

September 3–4
Main phase of geomagnetic disturbances from second CME ends; scattered auroral sightings continue, but with diminishing intensity.

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In ice-core data from Greenland and Antarctica, Kenneth G. McCracken of the University of Maryland has discovered sudden jumps in the concentration of trapped nitrate gases, which in recent decades appear to correlate with known blasts of solar particles. A nitrate anomaly found for 1859 stands out as the biggest of the past 500 years, with the severity roughly equivalent to the sum of all the major events of the past 40 years.

As violent as it was, the 1859 superstorm does not appear to have been qualitatively different from lesser events. The two of us, along with many other researchers, have reconstructed what happened back then from contemporary historical accounts as well as scaled-up measurements of milder storms in recent decades, which have been studied by modern satellites:

1. The gathering storm. On the sun, the preconditions for the 1859 superstorm involved the appearance of a large, near-equatorial sunspot group around the peak of the sunspot cycle. The sunspots were so large that astronomers such as Carrington could see them with the naked (but suitably protected) eye. At the time of the initial CME released by the storm, this sunspot group was opposite Earth, putting our planet squarely in the bull's-eye. The sun's aim need not be so exact, however. By the time a CME reaches Earth's orbit, it typically has fanned out to a width of some 50 million kilometers, thousands of times wider than our planet.

2. First blast. The superstorm released not one but two CMEs. The first may have taken the customary 40 to 60 hours to arrive. The magnetometer data from 1859 suggest that the magnetic field in the ejected plasma probably had a helical shape. When it first hit Earth, the field was pointing north. In this orientation, the field reinforced Earth's own magnetic field, which minimized its effects. The CME did compress Earth's magnetosphere—the region of near-Earth space where our planet's magnetic field dominates the sun's—and registered at magnetometer stations on the ground as what solar scientists call a sudden storm commencement. Otherwise it went unnoticed. As plasma continued to stream past Earth, however, its field slowly spun around. After 15 hours, it opposed rather than reinforced Earth's field, bringing our planet's north-pointing and the plasma cloud's south-pointing field lines into contact. The field lines then reconnected into a simpler shape, releasing huge amounts of stored energy. That is when the telegraph disruptions and auroral displays commenced. Within a day or two the plasma passed by Earth, and our planet's geomagnetic field returned to normal.

3. X-ray flare. The largest CMEs typically coincide with one or more intense flares, and the 1859 superstorm was no exception. The visible flare observed by Carrington and others on September 1 implied temperatures of nearly 50 million kelvins. Accordingly, it probably emitted not only visible light but also x-rays and gamma rays. It was the most brilliant solar flare ever recorded, bespeaking enormous energies released into the solar atmosphere. The radiation hit Earth after the light travel time of eight and a half minutes, long before the second CME. Had shortwave radios existed, they would have been rendered useless by energy deposition in the ionosphere, the high-altitude layer of ionized gas that reflects radio waves. The x-ray energy also heated the upper atmosphere and caused it to bloat out by tens or hundreds of kilometers.

4. Second blast. Before the ambient solar-wind plasma had time to fill in the cavity formed by the passage of the first CME, the sun fired off

IT'S RAINING PROTONS

Like terrestrial hurricanes and thunderstorms, solar storms can wreak havoc in multiple ways.

- Solar flares are relatively small-scale explosions that emit bursts of radiation. They cause enhanced radio absorption in the so-called D layer of Earth's ionosphere, interfering with Global Positioning System signals and shortwave reception. Flares also heat the upper atmosphere, puffing it up and increasing drag on satellites.
- Coronal mass ejections (CMEs) are giant bubbles of ionized gas. If Earth is caught in their crosshairs, they can induce electric currents that surge into pipelines, cables and electrical transformers.
- Solar proton events are floods of high-energy protons that occasionally accompany flares and CMEs. They can zap data in electronic circuits and give astronauts and airline passengers an extra dose of radiation.

AURORA BOREALIS, shown here in Njardvík, Iceland, is the most photogenic result of solar activity. These dramatic light shows occur when charged particles, mostly from the solar wind, collide with gases in Earth's upper atmosphere. The colors represent emissions from different chemical elements. Auroras are typically confined to polar regions but can dance across tropical skies during a major solar storm.

OPPOSITE PAGE: ILLUSTRATIONS BY MELISSA THOMAS; CARNEGIE INSTITUTION OF WASHINGTON (*sunspots*); SOHO/NASA (*coronal mass ejection* and *solar flare*); THIS PAGE: ARCTIC-IMAGES/CORBIS (*aurora*)

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a second CME. With little material to impede it, the CME reached Earth within 17 hours. This time the CME field pointed south as it hit, and the geomagnetic mayhem was immediate. Such was its violence that it compressed Earth's magnetosphere (which usually extends about 60,000 kilometers) to 7,000 kilometers or perhaps even into the upper stratosphere itself. The Van Allen radiation belts that encircle our planet were temporarily eliminated, and huge numbers of protons and electrons were dumped into the upper atmosphere. These particles may have accounted for the intense red auroras seen in much of the world.

5. Energetic protons. The solar flare and the intense CMEs also accelerated protons to energies of 30 million electron volts or higher. Across the Arctic, where Earth's magnetic field affords the least protection, these particles penetrated to an altitude of 50 kilometers and deposited additional energy in the ionosphere. According to Brian C. Thomas of Washburn University, the proton shower from the 1859 superstorm reduced stratospheric ozone by 5 percent. The layer took four years to recover. The most powerful protons, with energies above one billion electron volts, reacted with the nuclei of nitrogen and oxygen atoms in the air, spawning neutrons and creating the nitrate abundance anomalies. A rain of neutrons reached the ground in what is now called a ground level event, but no human technology was available to detect this onslaught. Fortunately, it was not hazardous to health.

6. Massive electric currents. As the auroras spread from the usual high latitudes to low latitudes, the accompanying ionospheric and auroral electric currents induced intense, continent-spanning currents in the ground. These currents found their way into telegraph circuitry. The multiampere, high-voltage discharges caused near electrocutions and were reported to have burned down several telegraph stations.

Toasted Satellites

When a large geomagnetic storm happens again, the most obvious victims will be satellites. Even under ordinary conditions, cosmic-ray particles erode solar panels and reduce power generation by about 2 percent annually. Incoming particles also interfere with satellite electronics. Many communications satellites, such as Anik E1 and E2 in 1994 and Telstar 401 in 1997, have been compromised or lost in this way. A large solar storm can cause one to three years' worth of satellite lifetime loss in a matter of hours and produce hundreds of glitches, ranging from errant but harmless commands to destructive electrostatic discharges.

To see how communications satellites might fare, we simulated 1,000 ways a superstorm might unfold, with intensities that varied from the worst storm of the Space Age (which occurred on October 20, 1989) to that of the 1859 superstorm. We found that the storms would not only degrade solar panels as expected but also lead to the significant loss of transponder revenue. The total cost would often exceed $20 billion. We assumed that satellite owners and designers would have mitigated the effects by maintaining plenty of spare transponder capacity and a 10 percent power margin at the time of their satellite's launch. Under less optimistic assumptions, the losses would approach $70 billion, which is comparable to a year's worth of revenue for all communications satellites. Even this figure does not include the collateral economic losses to the customers of the satellites.

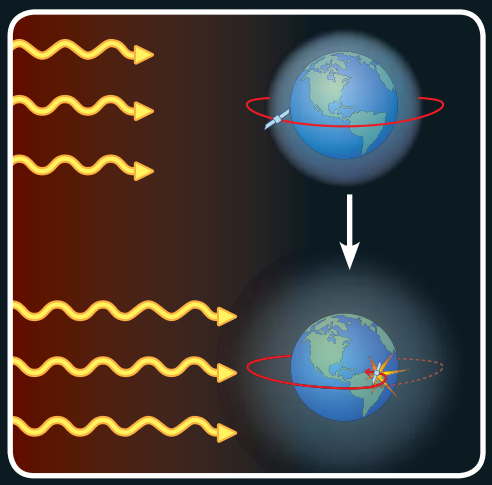
Fortunately, geosynchronous communications satellites are remarkably robust against once-a-decade events, and their life spans have

ILLUSTRATIONS BY MELISSA THOMAS

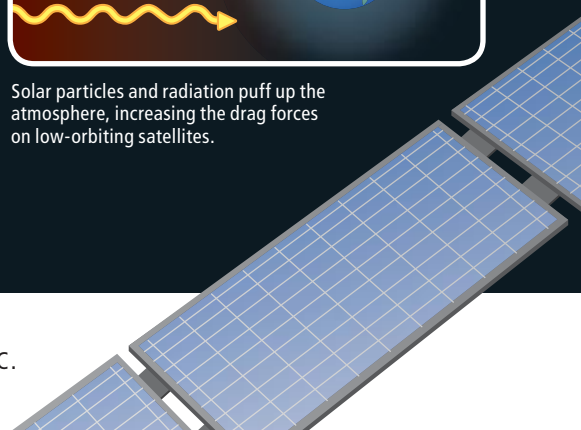
[EFFECTS ON SATELLITES]

Feeling the Full Brunt

The harshness of space takes a toll on satellites even at the best of times. A superstorm would cause years' worth of damage within a few hours.



Solar particles and radiation puff up the atmosphere, increasing the drag forces on low-orbiting satellites.



ZAPPING YOUR COMPUTER

A superstorm might well have strange effects on electronics. The high-energy protons that reach the ground produce neutrons that pass right through the shielding around satellite and avionics systems. (Most computer systems lack even this shielding.)

Extensive background radiation studies by IBM in the 1990s suggest that computers typically experience about one cosmic-ray-induced error per 256 megabytes of RAM per month. If so, a superstorm, with its unprecedented radiation fluxes, could cause widespread computer failures. Fortunately, in such instances most users could simply reboot.

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grown from barely five years in 1980 to nearly 17 years today. For solar panels, engineers have switched from silicon to gallium arsenide to increase power production and reduce mass. This move has also provided increased resistance to cosmic-ray damage. Moreover, satellite operators receive advanced storm warnings from the National Oceanic and Atmospheric Administration's Space Weather Prediction Center, which allows them to avoid complex satellite maneuvers or other changes during the time when a storm may arrive. These strategies would doubtless soften the blow of a major storm. To further harden satellites, engineers could thicken the shielding, lower the solar panel voltages to lessen the risk of runaway electrostatic discharges, add extra backup systems and make the software more robust to data corruption.

It is harder to guard against other superstorm effects. X-ray energy deposition would cause the atmosphere to expand, enhancing the drag forces on military and commercial imaging and communications satellites that orbit below 600 kilometers in altitude. Japan's Advanced Satellite for Cosmology and Astrophysics experienced just such conditions during the infamous Bastille Day storm on July 14, 2000, which set in motion a sequence of attitude and power losses that ultimately led to its premature reentry a few months later. During a superstorm, low-orbiting satellites would be at considerable risk of burning up in the atmosphere within weeks or months of the event.

Lights Out

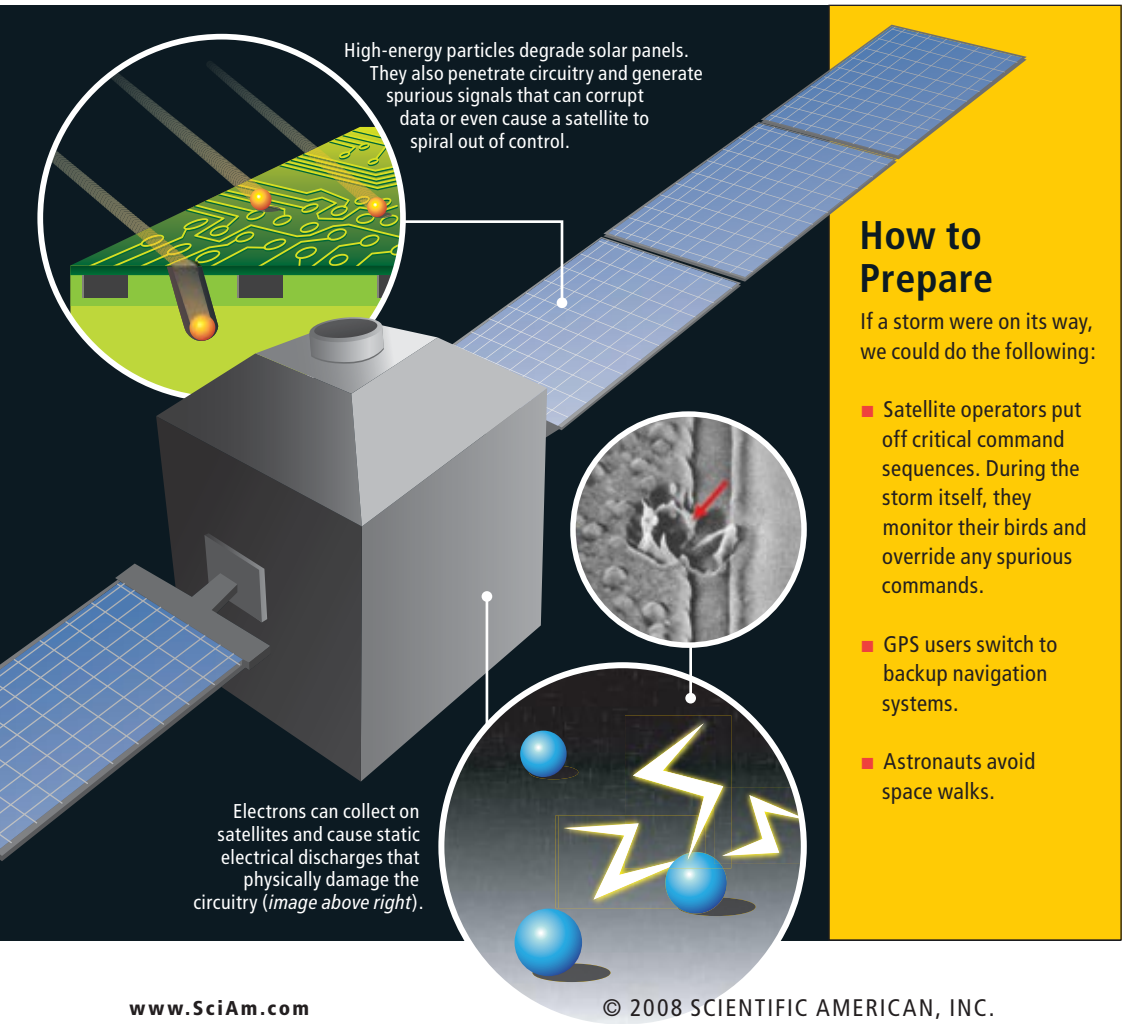
At least our satellites have been specifically designed to function under the vagaries of space weather. Power grids, in contrast, are fragile at the best of times. Every year, according to estimates by Kristina Hamachi-LaCommare and Joseph H. Eto, both at Lawrence Berkeley National Laboratory, the U.S. economy takes an $80-billion hit from localized blackouts and brownouts. Declining power margins over the past decade have also left less excess capacity to keep up with soaring demands.

During solar storms, entirely new problems arise. Large transformers are electrically grounded to Earth and thus susceptible to damage caused by geomagnetically induced direct cur-

[THE AUTHORS]

Sten F. Odenwald (*left*) is an astronomy professor at the Catholic University of America and a senior scientist at SP Systems in Greenbelt, Md. He is an award-winning science popularizer and author who works under contract at the NASA Goddard Space Flight Center. Odenwald's main areas of research are the cosmic infrared background and space weather phenomenology. His passion for astronomy was kindled at age 11 by *The Outer Limits* TV show.

James L. Green (*right*) is director of NASA's Planetary Science Division. He has studied planetary magnetospheres and is a co-investigator on the IMAGE magnetospheric mission. He enjoys history and is working on a publication about balloons in the American Civil War. It was his interest in this time period that led him to run across more than 200 newspaper articles about the 1859 storm.



How to Prepare

If a storm were on its way, we could do the following:

- Satellite operators put off critical command sequences. During the storm itself, they monitor their birds and override any spurious commands.
- GPS users switch to backup navigation systems.
- Astronauts avoid space walks.

SUSAN CLERMONT (*Odenwald*); COURTESY OF JAMES L. GREEN (*Green*); JPL (*satellite damage*)

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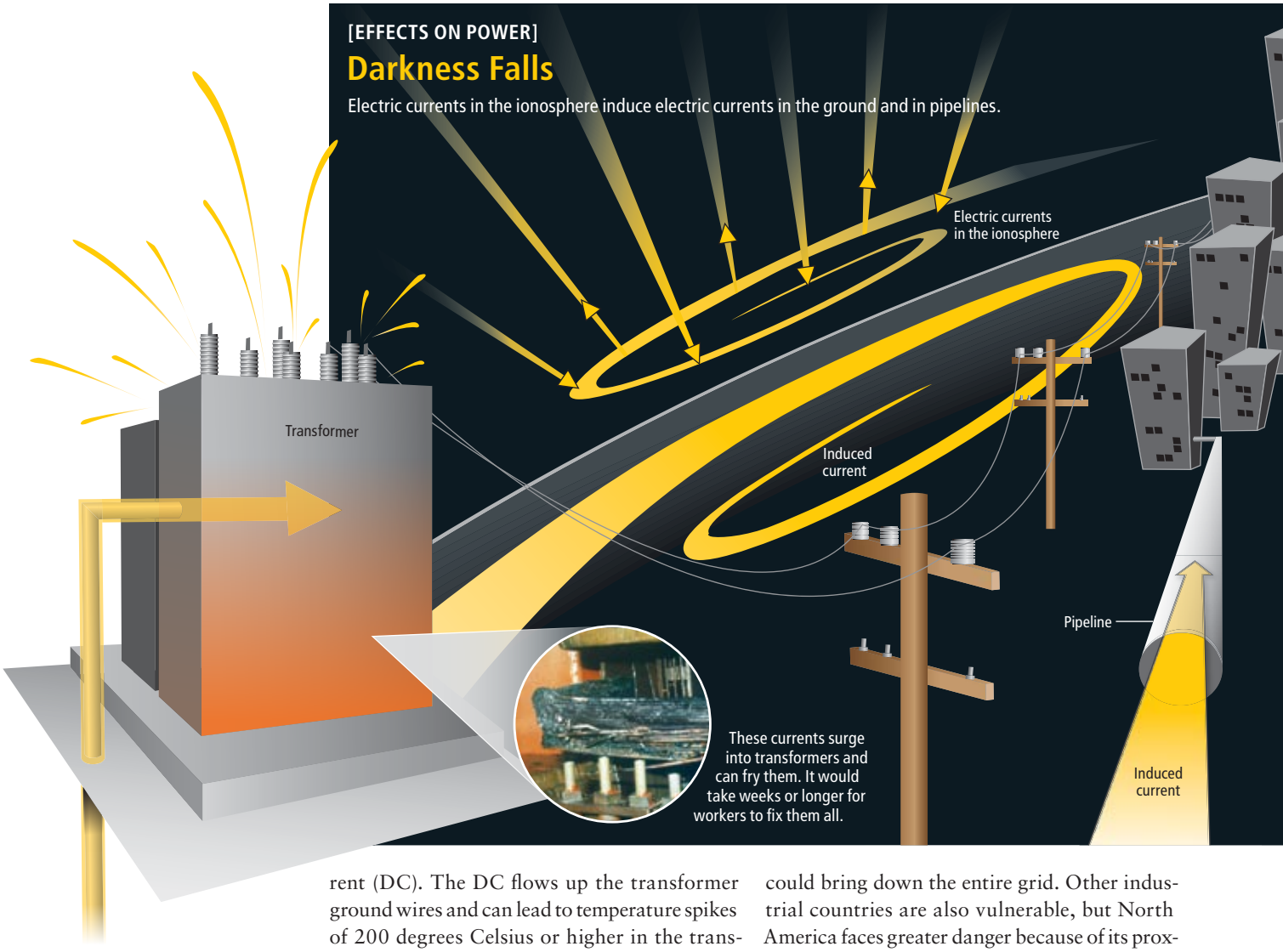

rent (DC). The DC flows up the transformer ground wires and can lead to temperature spikes of 200 degrees Celsius or higher in the transformer windings, causing coolant to vaporize and literally frying the transformer. Even if transformers avoid this fate, the induced current can cause their magnetic cores to saturate during one half of the alternating-current power cycle, distorting the 50- or 60-hertz waveforms. Some of the power is diverted to frequencies that electrical equipment cannot filter out. Instead of humming at a pure pitch, transformers would begin to chatter and screech. Because a magnetic storm affects transformers all over the country, the condition can rapidly escalate to a network-wide collapse of voltage regulation. Grids operate so close to the margin of failure that it would not take much to push them over.

According to studies by John G. Kappenman of Metatech Corporation, the magnetic storm of May 15, 1921, would have caused a blackout affecting half of North America had it happened today. A much larger storm, like that of 1859, could bring down the entire grid. Other industrial countries are also vulnerable, but North America faces greater danger because of its proximity to the north magnetic pole. Because of the physical damage to transformers, full recovery and replacement of damaged components might take weeks or even months. Kappenman testified to Congress in 2003 that "the ability to provide meaningful emergency aid and response to an impacted population that may be in excess of 100 million people will be a difficult challenge."

A superstorm will also interfere with radio signals, including those of the Global Positioning System (GPS) and related systems. Intense solar flares not only disturb the ionosphere, through which timing signals propagate, but also produce increased radio noise at GPS frequencies. The result would be position errors of 50 meters or more, rendering GPS useless for many military and civilian applications. A similar loss of precision occurred during the October 29, 2003, storm, which shut down the Wide Area Augmentation System, a radio network

WOULD ASTRONAUTS GET FRIED?

One piece of good news about superstorms is that the radiation dosage to astronauts in low-Earth orbit would probably not be life-threatening. Lawrence W. Townsend of the University of Tennessee calculated a superstorm dose of about 20 rads (0.2 gray), which is comparable to the 30-day cumulative exposure limits set by NASA.

On the other hand, this one-time event would still be more radiation than someone living on the ground would receive from natural environmental sources over the course of 70 years. Airline passengers might receive a dose equal to a CT scan.

ILLUSTRATIONS BY MELISSA THOMAS; COURTESY OF JOHN KAPPENMAN (*transformer melting* and *U.S. map*)

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The entire East Coast and much of the rest of the country would lose power. This map shows the blacked-out regions expected from a severe storm like that of 1921, which would induce ground fields of about 20 volts per kilometer. Scientists have yet to model the effects of a full-blown 1859-like storm on the power grid.

that improves the accuracy of GPS position estimates. Commercial aircraft had to resort to in-flight backup systems.

High-energy particles will interfere with aircraft radio communications, especially at high latitudes. United Airlines routinely monitors space weather conditions and has on several occasions diverted polar flights to lower altitudes and latitudes to escape radio interference. A superstorm might force the rerouting of hundreds of flights not just over the pole but also across Canada and the northern U.S. These adverse conditions might last a week.

Getting Ready

Ironically, society's increasing vulnerability to solar storms has coincided with decreasing public awareness. We recently surveyed newspaper coverage of space weather events since the 1840s and discovered that a significant change occurred around 1950. Before this time, magnetic storms, solar flares and their effects often received lavish, front-page stories in newspapers. The *Boston Globe* carried a two-inch headline "U.S. Hit by Magnetic Storm" on March 24, 1940. Since 1950, though, such stories have been buried on inside pages.

Even fairly minor storms are costly. In 2004 Kevin Forbes of the Catholic University of America and Orville Chris St. Cyr of the NASA Goddard Space Flight Center examined the electrical power market from June 1, 2000, to December 31, 2001, and concluded that solar storms increased the wholesale price of electricity during this period by approximately $500 million. Meanwhile the U.S. Department of Defense has estimated that solar disruptions to government satellites cost about $100 million a year. Furthermore, satellite insurers paid out nearly $2 billion between 1996 and 2005 to cover commercial satellite damages and losses, some of which were precipitated by adverse space weather.

We would be well served by more reliable warnings of solar and geomagnetic storms. With adequate warning, satellite operators can defer critical maneuvering and watch for anomalies that, without quick action, could escalate into critical emergencies. Airline pilots could prepare for an orderly schedule of flight diversions. Power grid operators could watch susceptible network components and make plans to minimize the time the grid might be out of commission.

Agencies such as NASA and the National Science Foundation have worked over the past 20 years to develop space-weather forecasting capabilities. Currently NOAA's Space Weather Prediction Center provides daily space weather reports to more than 1,000 businesses and government agencies. Its annual budget of $6 million is far less than the nearly $500 billion in revenues generated by the industries supported by these forecasts. But this capability relies on a hodgepodge of satellites designed more for research purposes than for efficient, long-term space weather monitoring.

Some researchers feel our ability to predict space weather is about where NOAA was in predicting atmospheric weather in the early 1950s. From a monitoring perspective, what are needed are inexpensive, long-term space buoys to monitor weather conditions using simple, off-the-shelf instruments. In the meantime, scientists have a long way to go to understand the physics of solar storms and to forecast their effects. If we really want to safeguard our technological infrastructure, we will have to redouble our investment in forecasting, modeling and basic research to batten down for the next solar tempest. ■

MORE TO EXPLORE

The 23rd Cycle: Learning to Live with a Stormy Star. Sten Odenwald. Columbia University Press, 2001.

The Fury of Space Storms. James L. Burch in *Scientific American,* Vol. 284, No. 4, pages 86–94; April 2001.

The Paradox of the Sun's Hot Corona. Bhola N. Dwivedi and Kenneth J. H. Phillips in *Scientific American,* Vol. 284, No. 6, pages 40–47; June 2001.

The Great Historical Geomagnetic Storm of 1859: A Modern Look. Edited by M. Shea and C. Robert Clauer in *Advances in Space Research,* Vol. 38, No. 2, pages 117–118; 2006.

The Mysterious Origins of Solar Flares. Gordon D. Holman in *Scientific American,* Vol. 294, No. 4, pages 38–45; April 2006.

General information about the impacts of solar storms can also be found at **www.solarstorms.org**

Sten F. Odenwald's popular Web site Astronomy Cafe is available at **www.astronomycafe.net**

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SELF-CLEANING MATERIALS

The lotus plant's magnificent ability to repel dirt has inspired a range of self-cleaning and antibacterial technologies that may also help control microfluidic "lab-on-a-chip" devices

By Peter Forbes

Wilhelm Barthlott of the University of Bonn in Germany, discoverer and developer of the "lotus effect," has a vision of a self-cleaning Manhattan, where a little rain washes the windows and walls of skyscrapers as clean as the immaculate lotus. Elsewhere, he sees tents and marquees using new textiles that stay equally spotless with no intervention from a human cleaner. He is not the only one with his sights set on a future populated with objects that rarely if ever need washing: in Japan, technologists are developing self-deodorizing and disinfectant surfaces for bathrooms and

JEAN-FRANCOIS PODEVIN

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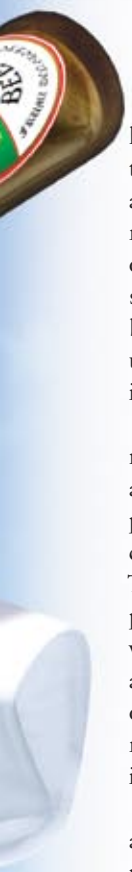

hospitals. Michael Rubner and Robert Cohen of the Massachusetts Institute of Technology envisage similar technologies keeping bathroom mirrors unfogged and controlling microfluidic "labs on a chip" (in which fluids move through microscopic pathways). Already with us are shirts, blouses, skirts and trousers that shrug off ketchup, mustard, red wine and coffee. A revolution in self-cleaning surfaces is under way.

The story of self-cleaning materials begins in nature with the sacred lotus (*Nelumbo nucifera*), a radiantly graceful aquatic perennial that has played an enormous role in the religions and cultures of India, Myanmar, China and Japan. The lotus is venerated because of its exceptional purity. It grows in muddy water, but its leaves, when they emerge, stand meters above the water and are seemingly never dirty. Drops of water on a lotus leaf have an unearthly sparkle, and rainwater washes dirt from that leaf more readily than from any other plant.

It is this last property that drew Barthlott's attention. In the 1970s he became excited by the possibilities of the scanning electron microscope, which had become commercially available in 1965 and offered vivid images down to the nanometer realm. At that scale of magnification, specks of dirt can ruin the picture, and so the samples have to be cleaned. But Barthlott noticed that some plants never seemed to need washing, and the prince of these was the lotus.

Barthlott realized that the effect is caused by the combination of two features of the leaf surface: its waxiness and the microscopic bumps (a few microns in size) that cover it. He knew from basic physics that the waxiness alone should make the leaves hydrophobic, or water-hating. On such a material, drops of water sit up high to minimize their area of contact with the material [*see bottom box on next page*]. Water on a more hydrophilic, or water-loving, substance spreads across it to maximize the contact area. For a hydrophilic surface, the contact angle (where the droplet's surface meets the material) is less than 30 degrees; a hydrophobic surface has a contact angle greater than 90 degrees.

In addition, he understood that the innumerable bumps take things a step further and cause the lotus surface to be superhydrophobic—the contact angle exceeds 150 degrees, and water on it forms nearly spherical droplets with very little surface contact that roll across it as easily as ball bearings would. The water sits on top of the bumps like a person lying on a bed of nails. Air trapped between the water and the leaf surface in the spaces around the bumps increases the contact angle, an effect that is described by the Cassie-Baxter equation, named after A.B.D. Cassie and S. Baxter, who first developed it in the 1940s.

Dirt, Barthlott saw, similarly touches only the peaks of the lotus leaf's bumps. Raindrops easily wet the dirt and roll it off the leaf. This discovery that microscopic bumps enhance cleanliness is wonderfully paradoxical. I learned at my mother's apron that "nooks and crannies harbor dirt"—capturing the conventional folk wisdom that if you want to keep things clean, keep them smooth. But contemplation of the lotus showed that this homily is not entirely true.

First and foremost a botanist, Barthlott initially did not see commercial possibilities in his observation of how the minuscule bumps keep lotus leaves spotless. In the 1980s, though, he realized that if rough, waxy surfaces could be synthesized, an artificial lotus effect could have many applications. He later patented the idea of constructing surfaces with microscopic raised areas to make them self-cleaning and registered Lotus Effect as a trademark.

Engineering a superhydrophobic surface on an object by using the lotus effect was not easy—the nature of a hydrophobic material is to repel, but this stuff that repels everything has to be made to stick to the object itself. Nevertheless, by the early 1990s Barthlott had created the "honey spoon": a spoon with a homemade microscopically rough silicone surface that allows honey to roll off, leaving none behind. This product finally convinced some large chemical companies that the technique was viable, and their research muscle was soon finding more ways to exploit the effect. The leading application so far is StoLotusan facade paint for buildings, introduced in 1999 by the German multinational Sto AG and a huge success. "Lotus Effect" is now a household name in Germany; last October the journal *Wirtschaftswoche* named it as one of the 50 most significant German inventions of recent years.

No More Restaurant Disasters

Say "self-cleaning…," and many people would add "clothes" as the missing word. We do not clean the outside of our houses very often, but washing clothes is always with us. After a tentative start, self-cleaning fabrics are popping up all over. It began with Nano-Care.

Nano-Care is a finish applied to fabrics developed by inventor and entrepreneur David Soane,

KEY CONCEPTS

- Microscopic bumps on a lotus leaf transform its waxy surface into an extremely water repellent, or superhydrophobic, material. Raindrops roll easily across such a surface, removing any dirt.
- Researchers have developed synthetic self-cleaning materials, some of which are based on this "lotus effect," whereas others employ the opposite property—superhydrophilicity—as well as catalytic chemical reactions.
- Future products may combine the two water affinity properties or use substances that can be switched back and forth to control the flow of liquids through microfluidic components.

—The Editors

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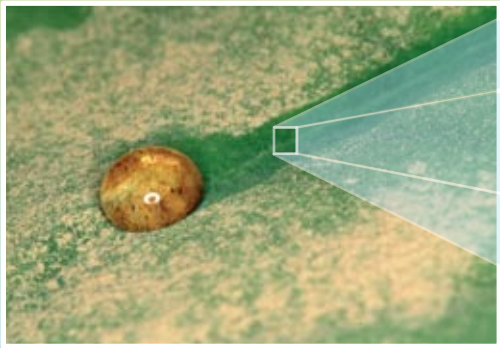
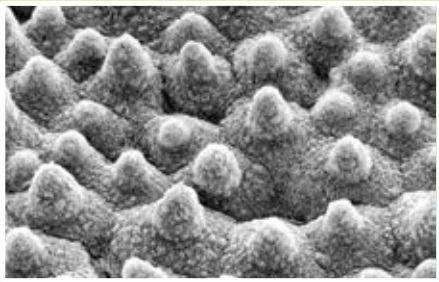
[INSPIRATION]

THE LOTUS EFFECT

The lotus leaf's remarkable ability to stay clean inspired development of self-cleaning materials.



▲ Water rolls across a leaf without sticking at all and carries away dirt.



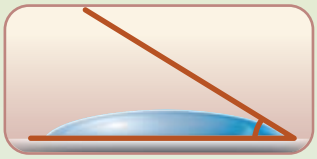
▲ Microscopic bumps (a few microns in size) all across the leaf's surface hold the key to its water-repelling properties. A rough coating of nanoscopic wax crystals on these bumps further increases the effect.

[THE BASICS]

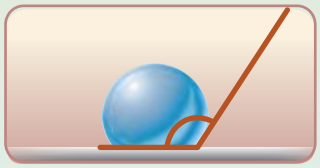
PHYSICS OF THE LOTUS

The lotus's self-cleaning effect stems from its surface being extremely hydrophobic (water-repelling). Whether a material is hydrophobic or hydrophilic (water-attracting) depends on the contact angle between the material and the surface of water.

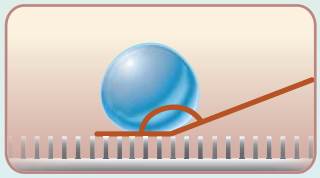
CONTACT ANGLES



HYDROPHILIC SURFACE: less than 30 degrees



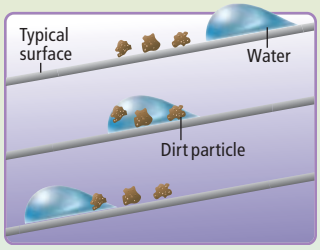
HYDROPHOBIC SURFACE: greater than 90 degrees



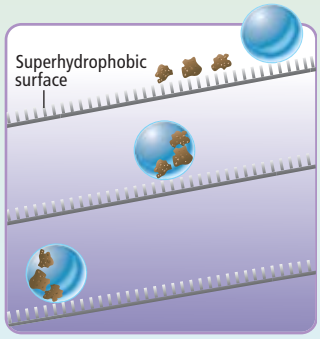
SUPERHYDROPHOBIC SURFACE: greater than 150 degrees

The large angle results from bumps that trap air between water and the surface, minimizing contact with the surface.

HOW THE LOTUS CLEANS ITSELF



On a typical surface (one not extremely hydrophilic or hydrophobic), a drop of water slides across and leaves most dirt particles sticking to the object.



On a superhydrophobic surface, a drop rolls across, picking up dirt and carrying it away. The water and dirt have greater affinity for each other than either does for the surface.

now made by his company Nano-Tex. Think of the fuzz on a peach; put the peach under the tap, and you will see the Nano-Care effect. Nano-Care's "fuzz" is made of minuscule whiskers and is attached to the cotton threads. The whiskers are so small—less than a thousandth of the height of lotus bumps—that the cotton threads are like great tree trunks in comparison.

Nano-Tex's rival is the Swiss firm Schoeller Textil AG, which calls its technology Nano-Sphere. The system has nanoscopic particles of silica or of a polymer on the clothing fibers, and these particles provide the lotuslike bumpy roughness.

Because many untested claims have been made to support nanotechnology products, standards institutions are beginning to set stringent tests for self-cleaning clothing that are based on these innovations. In October 2005 the German Hohenstein Research Institute, which offers tests and certifications to trade and industry around the world, announced that NanoSphere textiles were the first of such fabrics to pass a whole range of tests, including those examining water repellency and the ability of the fabric to maintain its performance after ordinary wash cycles and other wear and tear. In a test of my own, samples of NanoSphere showed an impressive ability to shrug off oily tomato sauces, coffee and red wine stains—some of the worst of the usual suspects.

Easy-clean clothes are becoming widely available, but buyers of marquees, awnings and sails are expected to constitute the biggest market (in terms of money spent) for lotus effect finishes. No one really wants to have to clean these large outside structures.

ANN SANDERSON (*illustrations*); NACIVET *Getty Images* (*top left*); WILHELM BARTHLOTT *University of Bonn* (*top center* and *top right*)

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Superwettability

The exploration of the lotus effect began as an attempt to understand the self-cleaning powers of one type of surface—waxy ones with microscopic or even nanoscale structures. This research has now broadened into an entire new science of wettability, self-cleaning and disinfection. Researchers realized that there might be many ways to make superhydrophobic surfaces and that superhydrophobicity's reverse—superhydrophilicity—might also be interesting. The leading player in superhydrophilicity is the mineral titanium dioxide, or titania.

Titania's journey to stardom began more than four decades ago with a property that has nothing to do with wettability. In 1967 Akira Fujishima, then a graduate student at the University of Tokyo, discovered that when exposed to ultraviolet light, titania could split water into hydrogen and oxygen. The splitting of water powered by light, or photolysis, has long been something of a holy grail because if it could be made to work efficiently, it could generate hydrogen cheaply enough to make that gas a viable, carbon-free substitute for fossil fuels. Fujishima and other researchers pursued the idea vigorously, but eventually they realized that achieving a commercial yield was a very distant prospect.

The studies did reveal that thin films of titania (in the range of nanometers to microns thick) work more efficiently than do larger particles. And, in 1990, after Fujishima teamed up with Kazuhito Hashimoto of the University of Tokyo and Toshiya Watanabe of the sanitary equipment manufacturer TOTO, he and his colleagues discovered that nanoscale thin films of titania activated by ultraviolet light have a photocatalytic effect, breaking down organic compounds—including those in the cell walls of bacteria—to carbon dioxide and water.

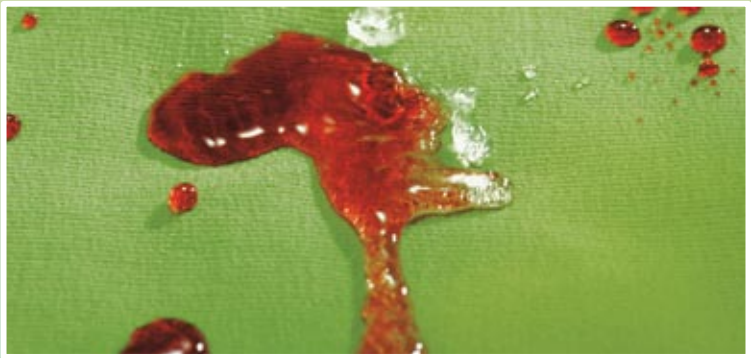
Titania is photocatalytic because it is a semiconductor, meaning that a moderate amount of energy is needed to lift an electron from the mineral's so-called valence band of filled energy levels across what is known as a band gap (composed of forbidden energy levels) into the empty "conduction band," where electrons can flow and carry a current. In titania's case, a photon of ultraviolet light with a wavelength of about 388 nanometers can do the trick, and in the process it produces two mobile charges: the electron that it hoists to the conduction band as well as the hole that is left behind in the valence band, which behaves much like a positively charged particle [*see box on next page*]. While these two charges are on the loose, they can interact with water and oxygen at the surface of the titania, producing superoxide radical anions (O_2^-) and hydroxyl radicals (OH)—highly reactive chemical species that can then convert organic compounds to carbon dioxide and water.

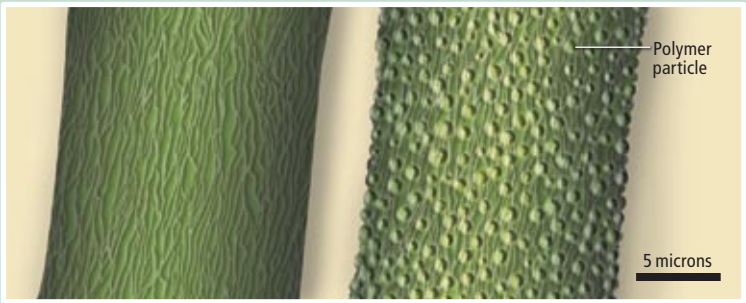
In the mid-1990s the three Japanese researchers made another crucial discovery about titania when they prepared a thin film from an aqueous suspension of titania particles and annealed it at 500 degrees Celsius. After the scientists exposed the resulting transparent coating to ultraviolet light, it had the extraordinary property of complete wettability—a contact angle of zero degrees—for both oil and water. The ultraviolet light had removed some of the oxygen atoms from the surface of the titania, resulting in a patchwork of nanoscale domains where hydroxyl groups became adsorbed, which produced the superhydrophilicity. The areas not in those domains were responsible for the great affinity for oil. The effect remained for several days after the ultraviolet exposure, but the titania slowly

[A LOTUS LESSON]

ONE WAY TO STAY CLEAN

Companies have made textiles that can shrug off water and food spills by being superhydrophobic like a lotus leaf (*top*). Modifications to the material's individual cotton fibers produce the effect. In one scheme (*bottom*), particles form bumps several hundred nanometers in size on the fibers. Many other products, such as facade paint and roofing tiles, have a microscopic or nanoscopic rough finish to induce the lotus effect.





Untreated cotton fiber Treated cotton fiber

LOVE-HATE RELATIONSHIPS

Some surfaces, spanning the gamut from water-loving to water-hating, and their approximate contact angles:

- Superhydrophilic: titania thin films, 0 degrees [*see box on next page*]
- Hydrophilic: standard window glass, 30 degrees
- Hydrophobic: Teflon, 100 degrees
- Superhydrophobic: lotus leaves, 160 degrees

NANO-SPHERE (*top*); DANIELA NAOMI MOLNAR (*bottom*)

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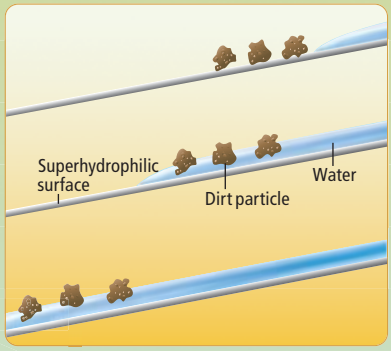
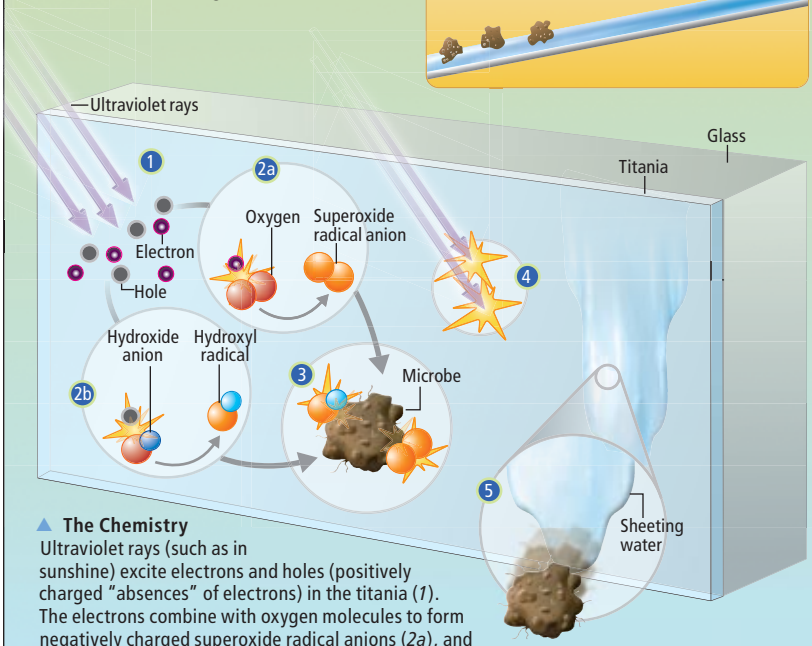
[AN OPPOSITE APPROACH]

SELF-CLEANING TITANIA

Thin films of titania have the very opposite property to the lotus—superhydrophilicity—yet they, too, shrug off dirt, and they are also antimicrobial.

What the Water Does ▶
Water on a superhydrophilic material forms a sheet across the surface and easily dislodges and removes dirt as it flows. Superhydrophilicity also prevents a surface from fogging because water spreads instead of forming the innumerable tiny droplets that constitute a fog.





▲ The Chemistry
Ultraviolet rays (such as in sunshine) excite electrons and holes (positively charged "absences" of electrons) in the titania (*1*). The electrons combine with oxygen molecules to form negatively charged superoxide radical anions (*2a*), and the holes combine with hydroxide anions from water to form neutral hydroxyl radicals (*2b*). These highly reactive species kill microbes and break down organic materials on the surface (*3*). The ultraviolet light also changes the structure of the titania film, making it superhydrophilic (*4*), which allows water to wash off dirt (*5*).

[THE AUTHOR]

Peter Forbes is a science writer living in London. His 2006 book, *The Gecko's Foot* (W. W. Norton), explored a variety of biomimetic, or bioinspired, technologies. He was also editor of *Scanning the Century: The Penguin Book of the Twentieth Century in Poetry* (Penguin, 2000).

reverted to its original state the longer it was kept in the dark.

Although it is the very opposite of the lotus leaf's repulsion of water, titania's superhydrophilicity turns out also to be good for self-cleaning: the water tends to spread across the whole surface, forming a sheet that can carry away dirt as it flows. The surface also resists fogging, because condensing water spreads out instead of becoming the thousands of tiny droplets that constitute a fog. The photocatalytic action of titania adds deodorizing and disinfection to the self-cleaning ability of coated items by breaking down organics and killing bacteria.

The titania-coating industry is now burgeoning. TOTO, for instance, produces a range of photocatalytic self-cleaning products, such as outdoor ceramic tiles, and it licenses the technology worldwide.

Because nanocoatings of titania are transparent, treated window glass was an obvious development. In 2001 Activ Glass, developed by Pilkington, the largest glass manufacturer in the U.K., became the first to hit the market. In general, glass is formed at about 1,600 degrees C on a bed of molten tin. To make Activ Glass, titanium tetrachloride vapor is passed over the glass at a later cooling stage, depositing a layer of titania finer than 20 nanometers thick. Activ Glass is fast becoming the glass of choice for conservatory roofs and vehicles' side mirrors in the U.K.

Unfortunately, ordinary window glass blocks the ultraviolet wavelengths that drive titania's photocatalytic activity, so titania nanolayers are less useful indoors than out. The answer is to "dope" the titania with other substances, just as silicon and other semiconductors are doped for electronics. Doping can decrease the material's band gap, which means that the somewhat longer wavelengths of indoor lighting can activate photocatalysis. In 1985 Shinri Sato of Hokkaido University in Japan serendipitously discovered the benefit of doping titania with nitrogen. Silver can also be used to dope the titania. Only in recent years, however, have these approaches been translated into commercial processes.

The antibacterial and deodorizing properties of doped titania are expected to have wide applications in kitchens and bathrooms. Titania is also being used in self-cleaning textiles and offers the advantage of removing odors. Various techniques have been devised to attach it to fabrics, including via direct chemical bonds.

Convergence of Opposites

The lotus-inspired materials and the titania-based thin films can be seen as opposite extremes rarely found in our everyday world where, as English poet Philip Larkin said, "nothing's made/As new or washed quite clean." For a long time, the techniques and materials were entirely different, and studies of the superhydrophobic effect and photocatalytic superhydrophilicity were totally separate. More recently, a remarkable convergence has occurred, with investigators working on combining the two effects and on producing both of them with very similar materials. Researchers are even exploring ways to get the same structure to switch from being superhydrophobic to being superhydrophilic, and vice versa.

An early hint of the convergence came in

DUNCAN PHILLIPS (*Forbes*); ANN SANDERSON (*illustrations*)

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2000 from titania pioneers Fujishima, Watanabe and Hashimoto. They wanted to use titania to extend the life of lotus effect surfaces. At first blush, this approach sounds destined for failure: titania's photocatalytic activity would be expected to attack the hydrophobic, waxy coatings of lotus surfaces and destroy the effect. And indeed, such attacks do happen with large concentrations of titania. But the group found that adding just a tiny amount of titania could significantly prolong lotus effect activity without greatly changing the high contact angle needed for the strong repellency.

In 2003 Rubner and Cohen's laboratory at M.I.T. discovered how a minor change in construction could determine whether a superhydrophobic or superhydrophilic surface was produced. During a visit to China that year, Rubner recalls, he "got excited about some superhydrophobic structures" that were mentioned at a meeting. On his return, he directed some of his group's members to attempt to make such structures. His lab had developed a layer-by-layer technique for making thin films out of a class of compounds called polyelectrolytes. Ordinary electrolytes are substances that when dissolved in water split up into positively and negatively charged ions; common salt or sulfuric acid would be examples. Polyelectrolytes are organic polymers, plastic materials that, unlike most polymers, carry charge, either positive or negative. Rubner and Cohen stacked up alternating layers of positively charged poly(allylamine hydrochloride) and negatively charged silica particles. (In earlier work they had used coatings with silica particles to mimic the lotus's rough hydrophobic surface.)

To these multilayers, they added a final coating of silicone (a hydrophobic material), but along the way they noticed something intriguing: before they applied the silicone, the layer cake was actually superhydro*philic*. In Rubner and Cohen's experiments, the silica layers had created a vast warren of nanopores, forming a sponge that soaked up any surface water instantly, a phenomenon called nanowicking. The silica-polymer multilayers they developed will not fog even if held over steaming water. If the pores get saturated, water starts running off the edge. When the wet conditions abate, the water in the nanowicks slowly evaporates away.

Because glass itself is mostly silica, the multilayers are well suited for application to glass. The superhydrophilic coatings are not only transparent and antifogging but are also antireflective. Rubner's team is working with industrial partners to commercialize the discovery. Applications of this work include bathroom mirrors that never fog and car windshields that never need a blower on cold, wet winter mornings. Unlike titania, Rubner's surfaces work equally well in the light or dark.

Smart Beetles

Millions of years before scientists put together the lotus effect and superwettability for technological applications, a small beetle of the Namib Desert in southern Africa was busy applying the two effects to another end: collecting water for its own survival.

The Namib Desert is extremely inhospitable. The daytime temperatures can reach 50 degrees C (about 120 degrees Fahrenheit), and rain is very scarce. About the only source of moisture is thick morning fogs, typically driven by a stiff breeze. The beetle, *Stenocara* sp., has developed

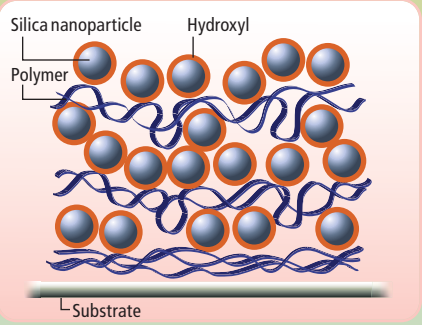
Antibacterial and deodorizing properties of doped titania are expected to have wide applications in kitchens and bathrooms.

[MULTILAYER TECHNOLOGY]

ANTIFOGGING COATINGS

Massachusetts Institute of Technology researchers have developed multilayered superhydrophilic coatings that are antifogging and antireflective.

Alternating layers of polymer and nanoparticles of silica (which have hydroxyl groups bound to their surface) form a superhydrophilic coating that can be applied to glass and other materials. The coating surface is rough at the nanoscale, but the hydroxyl is strongly hydrophilic, which helps nanoscopic pores throughout the multilayers to soak up water like a sponge, instantly wicking it away from the surface.



A glass slide treated with these multilayers remains clear even when it is chilled in a fridge and then put in warm, humid air (*left*)—conditions that thoroughly cloud untreated glass (*right*).

MICHAEL RUBNER *Massachusetts Institute of Technology (lotus under glass)*; ANN SANDERSON *(illustration)*

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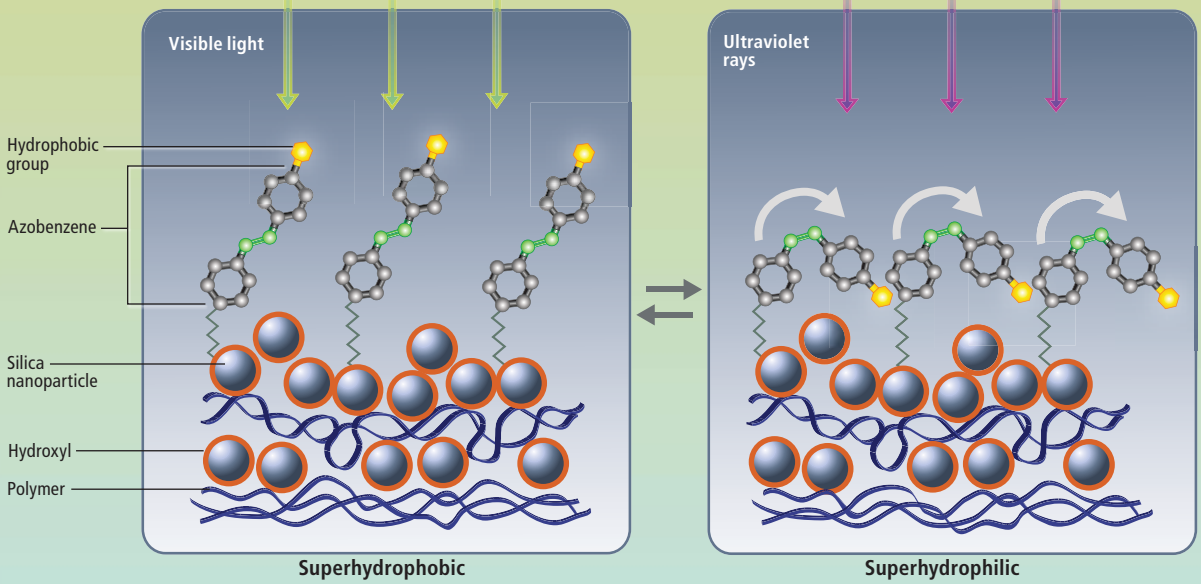
[BEYOND SELF-CLEANING]

SWITCHABLE SURFACES

By switching the hydrophobicity of precise locations on a surface, scientists hope to control fluids moving through networks of microscopic channels on so-called microfluidic chips.



▲ Researchers at Pohang University of Science and Technology in South Korea attached a molecule based on azobenzene on top of polymer-silica multilayers [*see box on preceding page*]. A hydrophobic group on the end of the molecule, along with the roughness of the layers, makes the surface superhydrophobic (*left*). In ultraviolet light, however, the molecule bends, burying the hydrophobic group and making the surface superhydrophilic (*right*). Visible light promptly restores the original condition.

◀ On a treated surface, water clings to the areas made superhydrophilic by square spots of ultraviolet light. Water placed on other regions forms the characteristic nearly spherical drops of the lotus effect.

The new science of superwettability makes possible applications that go well beyond that of keeping a surface clean.

a way to harvest the water in those mists: it squats with its head down and its back up, facing the foggy wind. Water condenses on its back and trickles down into its mouth. The scientific rationale behind the *Stenocara* beetle's technique has inspired ideas for water-collecting technology in arid regions.

As so often happens, the beetle's mechanism was discovered by a researcher looking for something else. In 2001 zoologist Andrew R. Parker, then at the University of Oxford, came across a photograph of beetles eating a locust in the Namib Desert. The locust, which had been blown there by the region's strong winds, would have perished from the heat as soon as it hit the sand. Yet the beetles feasting on this literal windfall were obviously comfortable. Parker guessed that they must have sophisticated heat-reflection surfaces.

Indeed, *Stenocara* beetles do reflect heat, but when Parker examined their backs, he immediately suspected that some adaptation of the lotus effect was at work in their morning water-collection process. Most of the back of a *Stenocara* beetle is a bumpy, waxy, superhydrophobic surface. The tops of the bumps, though, are free of wax and are hydrophilic. Those hydrophilic spots capture water from the fog, forming droplets that quickly grow large enough for gravity and the surrounding superhydrophobic area to dislodge them. In lab experiments with glass slides, Parker found that this arrangement of regions is about twice as efficient as a smooth, uniform surface, regardless of whether it is hydrophilic or hydrophobic.

Parker has patented a design to imitate the beetle's process, and the U.K. defense contractor QinetiQ is developing it for fog harvesting in arid regions. Others are also trying to mimic *Stenocara*. In 2006 Rubner and Cohen's team

KILWON CHO *Pohang University of Science and Technology* (*switchable surface*); ANN SANDERSON (*illustrations*)

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created superhydrophilic spots of silica on superhydrophobic multilayers. This is one better than the beetles, whose spots are merely hydrophilic.

The new science of superwettability, as exemplified by the artificial *Stenocara* surfaces, makes it possible to control liquid flows at the microscale and the nanoscale, for use in applications that go well beyond that of keeping a surface clean. Rubner says: "Once you realize that textured surfaces can be either superhydrophobic or superhydrophilic depending on the top's surface chemistry, all sorts of possibilities open up." Of particular use would be switchable surfaces—ones whose wettability can be reversed at precise locations.

Such tunability might be achieved by many means: ultraviolet light, electricity, temperature, solvent and acidity. In 2006 a team led by Kilwon Cho of Pohang University of Science and Technology in South Korea achieved complete switchability by adding a compound based on the molecule azobenzene to the siliconized (superhydrophobic) surface of a silica-polyelectrolyte multilayer. The new surface is also superhydrophobic, but under ultraviolet light the azobenzene compound changes configuration and converts it to superhydrophilic [*see box on opposite page*].

Visible light reverses the change. This kind of control could have major applications in the field of microfluidics, such as the microarrays now used for drug screening and other biochemical tests [see "Big Lab on a Tiny Chip," by Charles Q. Choi; Scientific American, October 2007]. For instance, hydrophilic pathways could be closed or opened by switching parts of them to be hydrophobic or hydrophilic.

Staying Dry Underwater

It is one of the pleasant surprises of the 21st century that the radiance of the lotus is penetrating into previously unknown nooks and crannies, as well as beyond self-cleaning applications.

Barthlott, who saw the potential in a drop of water on a lotus leaf, now sees almost limitless vistas. But he warns those who want to translate from nature to technology that they are likely to encounter great skepticism, as he did. "Do trust your own eyes and *not* the textbooks, and if your observation is repeatedly confirmed, publish it," he advises. "But take a deep breath—expect rejections of your manuscript."

He is, not surprisingly, a passionate advocate for biodiversity, pointing out that many other plants and animals may have useful properties—possibly including species unknown to science and in danger of extinction. His current research involves superhydrophobicity underwater. After studying how plants such as the water lettuce *Pistia* and the floating fern *Salvinia* trap air on their leaf surfaces, Barthlott created fabrics that stay dry underwater for four days. An unwettable swimsuit is in prospect. The big prize would be to reduce the drag on ships' hulls. The lotus collects no dirt, but it is garnering an impressive string of patents. ■

[COMBINED EFFECTS]

WATER HARVESTING

Researchers inspired by a desert beetle are developing devices that will use a combination of the lotus effect and superhydrophilicity to harvest water from the air in remote, arid regions.

The beetle *Stenocara* sp. gathers water from wind-driven morning fogs in Africa's Namib Desert by crouching with its back raised facing the wind (*left*). Its back is mostly superhydrophobic thanks to 0.5-millimeter bumps and the microscopic roughness of its waxy surface (*below*). Water droplets form, however, on tiny hydrophilic areas at the peaks of the bumps and roll down to the beetle's mouth.

BIOMIMETICS

Bio-inspirations for technologies under development include:

Nanoscopic hairs (*below*) that allow geckos to walk on the ceiling.

Mussel glue, which sets underwater.

Spider silk, which is tougher than steel weight for weight.

MORE TO EXPLORE

The Lotus Effect. Hans Christian von Baeyer in *The Sciences,* Vol. 40, No. 1, pages 12–15; January/February 2000.

Water Capture by a Desert Beetle. Andrew R. Parker and Chris R. Lawrence in *Nature,* Vol. 414, pages 33–34; November 1, 2001.

Self-Cleaning Surfaces—Virtual Realities. Ralf Blossey in *Nature Materials,* Vol. 2, No. 5, pages 301–306; May 2003.

The Gecko's Foot. Peter Forbes. W. W. Norton, 2006.

Patterned Superhydrophobic Surfaces: Toward a Synthetic Mimic of the Namib Desert Beetle. Lei Zhai et al. in *Nano Letters,* Vol. 6, No. 6, pages 1213–1217; June 2006.

The Dream of Staying Clean: Lotus and Biomimetic Surfaces. Andreas Solga, Zdenek Cerman, Boris F. Striffler, Manuel Spaeth and Wilhelm Barthlott in *Bioinspiration & Biomimetics,* Vol. 2, No. 4, pages S126–S134; December 2007.

COURTESY OF ANDREW R. PARKER (*beetle*); "WATER CAPTURE BY A DESERT BEETLE," BY ANDREW R. PARKER AND CHRIS R. LAWRENCE, IN *NATURE,* VOL. 414, PAGES 33–34; NOVEMBER 1, 2001 (*beetle surface*); REUTERS/CORBIS (*full-size gecko*); VISUALS UNLIMITED/CORBIS (*gecko foot micrograph*)

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Magnifying Taste

Compounds that enhance the sweet and salty flavors of foods could combat obesity and heart disease

By Melinda Wenner

Humans are hardwired to love the sweet, savory and salty foods that provide the energy, protein and electrolytes we need. In an age of mass-produced products laden with sugar and salt, however, our taste proclivities can readily bring on obesity, heart disease and type 2 diabetes—all among society's biggest health problems.

But what if a handful of tiny compounds could fool our brains into eating differently? That is the idea behind the new science of flavor modulation. Scientists who have unlocked the long-standing mystery of taste biology are developing inexpensive yet potent compounds that make foods taste sweeter, saltier and more savory (heartier) than they really are. By adding tiny amounts of these modulators to traditional foods, manufacturers could reduce the amount of sugar, salt and monosodium glutamate (MSG) needed to satisfy, resulting in healthier products.

San Diego–based Senomyx is at the forefront of this new technology, and large companies are responding. Nestlé started incorporating Senomyx's savory flavor modulators in its bouillon products last year. Coca-Cola and Cadbury aim to begin using Senomyx's compounds early in 2009.

Senomyx is also designing bitterness blockers to make less palatable foods taste better, which could broaden the world's sources of nutrients. For example, companies could use soy protein more widely, potentially feeding more people, if they could mask its bitter aftertaste. Such blockers could also make medicines taste better, which would encourage people to take them.

By tricking our taste buds, Senomyx could save food makers a heaping teaspoon of money, allowing them to replace volumes of sugar, salt and other ingredients with minute quantities of cheap compounds. More important, taste modulators could revolutionize our health, making what tastes good to us actually *be* good for us.

The Taste Bud, Newly Understood

The quest for flavor modulators began in 1996, when Charles Zuker, a biology professor at the University of California, San Diego, realized that the prevailing literature on taste biology was potentially wrong. Humans sense five taste qualities: sweet, salty, bitter, sour and savory (also called umami, which roughly translates from Japanese into "delicious flavor"). Most children had been taught that the tongue is partitioned into regions that each detect one type of flavor. But work at the time showed that taste buds across the tongue and mouth contain small groups of cells that enable each bud to detect every flavor. Zuker agreed but could not swallow the corollary that every taste cell in a taste bud can distinguish among the five flavors.

To Zuker, it did not make evolutionary sense for one cell to be responsible for detecting the presence of something good, like sugar, and something bad, like poison (bitter). Many sensory cells can differentiate among opposing stimuli, but each of our sensory domains also includes cells whose primary job is to respond to one type of stimulus, such as skin cells that

KEY CONCEPTS

- Researchers have discovered tiny compounds that make foods taste sweeter, saltier and more savory than they really are, which could reduce the sugar, salt and monosodium glutamate typically added.
- Several of these taste enhancers are being tested in commercial foods.
- Whether people will consume fewer calories if their foods become tastier remains to be seen; people might eat lots of sweet foods for reasons that have nothing to do with taste.

—The Editors

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NICK ROTONDO

only respond to a certain temperature range. Zuker could not come to grips with the notion that a single taste cell "could evoke diametrically opposed behaviors—like attraction and aversion, or life and death," he recalls. Instead, he thought, a taste bud would be home to sweet cells, salt cells, bitter cells, and so on.

If taste cells were this specific, they would also be easier to tinker with—which could have big implications for the food industry. Zuker reasoned that taste cells would have specific sensors, or receptors, on their outer membrane. A salt receptor would lock onto a salt molecule but not a sweet or bitter molecule. But he had no evidence for his theory.

As a first step, Zuker had to isolate the actual taste receptors, which no one had ever done. He and his U.C.S.D. colleagues removed taste cells from the tongues of laboratory mice and compared the genes that were expressed (that is, gave rise to proteins) in each cell. Ultimately, the researchers found genes that coded for two proteins that had not been discovered before. Zuker could tell by their structures that the two proteins sat on the cell surface and probably functioned as receptors, and he named them T1R1 and T1R2.

But when Zuker tried to understand what the two proteins did, he hit a wall. Neither functioned by itself as a complete taste receptor. Zuker remembered that mice vary in their preferences for sweet foods—some barely like them at all. Previous studies had shown that such apathetic mice have a genetic defect. Zuker studied these mice and, sure enough, came across another new receptor candidate. And the gene for this protein, T1R3, was indeed the gene that differed among nonsweet-loving mice and normal mice. When he introduced a functional copy of the related gene into the taste cells of the defective mice, it triggered a love for sugar.

With a few more experiments, Zuker and his colleagues revealed the structure and function of the sweet and savory taste receptors. Each kind of receptor contained two parts. The sweet one consisted of T1R2 and T1R3; the savory comprised T1R1 and T1R3. Soon afterward, Zuker identified the bitter receptor units, too—all 25 of them—as well as the receptor responsible for detecting sour. In every case, each taste cell contained the receptors for just one taste.

Zuker realized that, beyond providing insights into basic biology, his discoveries would allow scientists to design compounds that interacted only with, say, the sweet receptor or the salt receptor, affecting taste perception in specific ways. "The basic tools to begin to experimentally modulate the way the taste system operates became feasible," he says. "We thought, here perhaps we have an opportunity to help make a difference." In 1998 Zuker and some associates started a company that became Senomyx.

Flavors by the Thousands

In the past, food companies identified new flavor compounds through trial-and-error experiments, with humans tasting the results one at a time. The process was tedious; companies could test at most a few thousand compounds a year.

But using Zuker's taste-receptor structure made it possible to rapidly identify new flavor modulators. Taking a lead from the plastic arrays with many tiny receptacles that pharmaceutical companies use to screen for new drugs, Zuker devised arrays of thousands of artificial "taste cells," each receptacle containing one kind of taste receptor. He then introduced thousands of potential flavor-modulating compounds

THE ELUSIVE UMAMI

Although it was discovered a century ago, umami still struggles for acceptance as the fifth basic taste the tongue recognizes. The term is Japanese for "savory" or "deliciousness." It is typically applied to meats, cheeses, broth and other protein-heavy foods to describe their hearty nature. The sensation may be more subtle than salty or sweet, but researchers maintain it is unique and not a combination of any of the other basic tastes.

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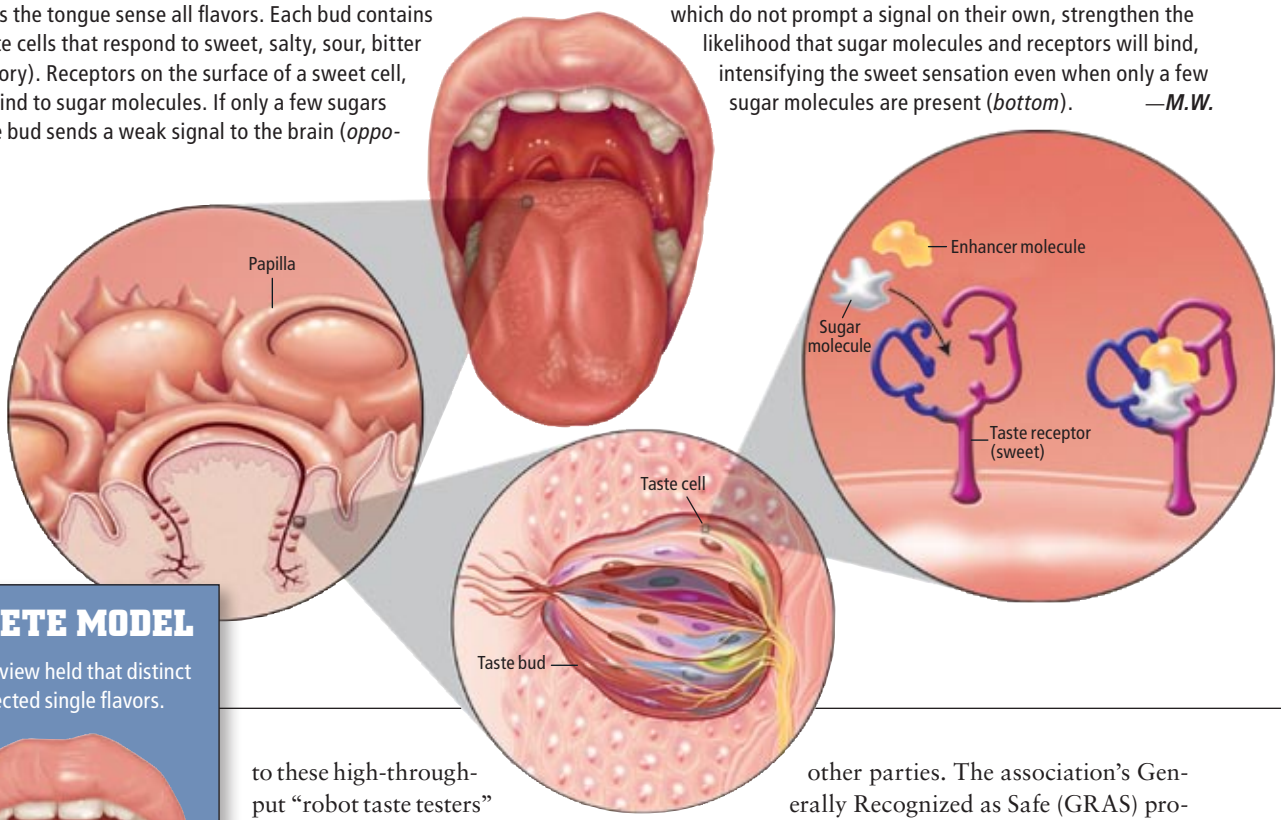
[HOW IT WORKS]

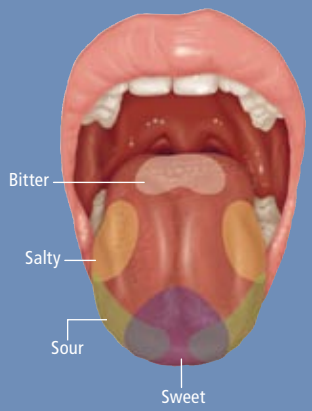
ENHANCING TASTE

Contrary to old models (*bottom left*), the tongue does not have regions that detect one type of flavor. Instead taste buds embedded in papilla (*bumps*) across the tongue sense all flavors. Each bud contains elongated taste cells that respond to sweet, salty, sour, bitter or umami (savory). Receptors on the surface of a sweet cell, for example, bind to sugar molecules. If only a few sugars are bound, the bud sends a weak signal to the brain (*opposite page, top*); if more sugars are present, more binding will cause a stronger signal of "sweet" (*middle*). Taste enhancer molecules, which do not prompt a signal on their own, strengthen the likelihood that sugar molecules and receptors will bind, intensifying the sweet sensation even when only a few sugar molecules are present (*bottom*). —***M.W.***



OBSOLETE MODEL

Wrong: Old view held that distinct regions detected single flavors.



to these high-throughput "robot taste testers" to see which ones interacted with which cells.

Today Senomyx has a library of 500,000 synthetic and natural compounds. "We can look at hundreds and thousands of different compounds and ingredients and can find a needle in the haystack," says Mark Zoller, the company's chief scientific officer. After identifying a compound that interacts uniquely with a taste cell, employees use the screening process to further improve its physical properties. Some compounds might need to dissolve in liquids or to retain their effects when heated. Many must remain stable in products for months on end. Senomyx develops assays to test for such characteristics, and "we can actually put the new sample in a cereal flake and see how it behaves and how it tastes," says vice president Gwen Rosenberg.

The company patents promising compounds and begins safety certification by sending information to the Flavor and Extract Manufacturers Association in Washington, D.C., an organization of flavor manufacturers, ingredient suppliers and other parties. The association's Generally Recognized as Safe (GRAS) program was established by the Food and Drug Administration in 1960 to oversee safety assessments of flavor compounds consumed in small amounts. Because the quantities are so minute, the compounds do not have to go through the more rigorous FDA safety process required for food "additives." When Senomyx submits information about a new compound, a panel of independent scientists decides, based on its chemistry, whether it will be safe to consume.

Although the process can take two years, some critics question its validity. Michael Jacobson, executive director of the Center for Science in the Public Interest in Washington, D.C., says the GRAS process "certainly is a case of the fox guarding the chicken coop." He does acknowledge that "flavorings typically have been innocuous chemicals used in small amounts" and that there is no history of safety problems.

Sweet Enhancement

Better sweeteners are at the forefront of Senomyx's work. The low-calorie sugar substitutes available today, such as aspartame, sucralose and saccharin, often have bitter aftertastes at

COLD AND CREAMY

Beyond manipulating the five basic tastes, researchers at Senomyx are developing compounds that, like menthol, feel "cold" on the tongue. They are also exploring the perception of "fatty" and "creamy" flavors. "This is really brand-new science," says vice president Gwen Rosenberg. "That's part of the excitement—nobody really has done this before."

ALICE Y. CHEN

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Few sugar molecules present; weak taste

Many sugars present; strong taste

Few sugars plus enhancers; strong taste

the high concentrations at which they are needed. "From a sensory point of view, they're not ideal," says Gary Beauchamp, director of the Monell Chemical Senses Center in Philadelphia. Diet sodas, for example, never taste quite as good as the real thing because the bitter aftertaste alters the brain's perception. If food companies could use less of the substitute, the bitter taste pathway would not be activated. (Coke Zero, which reportedly tastes better than Diet Coke, uses a mixture of sweeteners with less combined volume; the lower amount avoids activating the bitter receptor.)

With the ability to test so many compounds, Zuker realized Senomyx could identify molecules that did not have any flavor on their own but interacted with sweeteners and sweet receptors to enhance the perception. "We thought, my God, if we have the receptors, maybe we can find clever ways to make a little bit of sugar taste as if you have a lot," he says.

After screening 200,000 compounds, Senomyx researchers identified one that makes sucralose taste four times sweeter. The modulator recently completed the taste association's approval process and could be added to products in early 2009. The potential market is huge: an estimated 5,000 retail products currently contain sucralose. Senomyx has also found a sugar enhancer that makes sucrose, or table sugar, taste more than twice as sweet. In this way, Senomyx could cut the calories in foods yet ensure that they taste the same. And diet foods could taste even better than they do now.

Similarly, Senomyx's first savory enhancer is already in some Nestlé products. It makes foods taste heartier—a trait common to protein-rich foods such as meats and cheeses as well as snacks such as flavored potato chips—without lots of the MSG usually added to achieve this effect.

Bitter and Salty, Too

Senomyx is also developing bitter blockers that could broaden the use of soy proteins, as well as rid cocoa of its bitter aftertaste, lessening the sugar that manufacturers add to cocoa-based products. Such blockers could also aid drug companies that are trying to develop "pharmaceutical crops," such as rice and soybeans that contain oral vaccines for hepatitis B and other diseases. These crops might be grown in developing countries where access to vaccination is limited, but if the medicinal component makes them taste bad, local people will not eat them. A blocker would make the food palatable; of course, it would have to be affordable.

Another company, Redpoint Bio in Ewing, N.J., is developing bitter blockers using a slightly different approach. Instead of hunting for compounds that affect receptors on a taste cell's surface, the firm is seeking compounds that interact with signal pathways inside such cells. One target is a common ion channel called TRPM5; Redpoint is looking for compounds that either block or activate it. The company is collaborating with Coca-Cola and with Givaudan, a Swiss flavor and fragrance company, and anticipates that foods containing its compounds will be on grocery shelves within two years.

Salt is another grail because it is linked to cardiovascular disease. This year Senomyx identified the primary receptor responsible for salt perception: a pore or channel that spans the membrane of a taste cell, allowing sodium and hydrogen ions inside. Compounds that interact with the channel could enhance the potency of salt's effect. Reducing salt intake by even a small amount "could have a significant impact on both health and quality of life," says Zuker, who has stayed at U.C.S.D. while being a scientific adviser to Senomyx. If it is so hard to change people's eating habits, he reasons, then it makes sense to change their perceptions instead. In a few years, consumers might find themselves eating foods with a fraction of the calories and salt they once had, without noticing the difference.

Whether people will actually consume fewer calories if their foods become tastier and healthier remains to be seen, however. "That's a tough question, a very controversial one," Monell's Beauchamp says. People might consume lots of sweet food for reasons that have nothing to do with taste. Monell, which has received some funding from Senomyx, is studying how food and flavor preferences differ among people; how flavor affects digestion, metabolism and appetite; and how the body controls eating behavior. Preliminary findings, for example, suggest that our flavor preferences are essentially solidified by the age of three months and that a mother's meals during pregnancy and breast-feeding influence the foods her offspring end up enjoying. But the link between flavor preferences and satiety is not yet clear, Senomyx's Rosenberg acknowledges: "Satiety is a complex issue, and more work needs to be done." ■

Melinda Wenner is a freelance science writer based in New York City.

MORE TO EXPLORE

Taste Perception: Cracking the Code. Jane Bradbury in *PLoS Biology,* Vol. 2, No. 3, pages 0295–0297; March 16, 2004.

The Search for Sweet: Building a Better Sugar Substitute. Burkhard Bilger in *New Yorker,* page 40; May 22, 2006.

The Receptors and Cells for Mammalian Taste. Jayaram Chandrashekar, Mark A. Hoon, Nicholas J. P. Ryba and Charles S. Zuker in *Nature,* Vol. 444, pages 288–294; November 16, 2006.

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No More Cloning Around

Like many stem cell pioneers, Ian Wilmut, the creator of Dolly the sheep, has jumped to an alternative approach. Is this the beginning of the end for embryonic cloning? BY SALLY LEHRMAN

Sitting by the window of a posh coastal hotel in Half Moon Bay, Calif., wearing a baby-blue sweater and khakis, Ian Wilmut doesn't project the image of a scientist who pulled off one of the most dramatic experiments in modern biology. When he and his collaborators unveiled Dolly the cloned sheep in 1997, they ignited the embryonic stem cell research field, struck awe in the public and set off a panic about the imminent cloning of humans. "Dolly was a big surprise to everyone," recalls stem cell biologist Thomas Zwaka of the Center for Cell and Gene Therapy at the Baylor College of Medicine. Cloned frogs had refused to grow past the tadpole stage, and a seeming success in mice had proved to be a fake. According to scientific consensus back then, cloning adult mammals by the method Wilmut used was biologically impossible.

As Dolly matured, the cloning technology that created her—called somatic cell nuclear transfer (SCNT)—grew into a rich research enterprise. Scientists hoped to eventually be able to take a patient's cell, place its nucleus into an unfertilized human egg and then harvest embryonic stem cells to treat intractable conditions such as Parkinson's disease. But the first human clinical trial continues to seem remote, with embryonic cloning constrained by a federal funding ban, deeply controversial ethical issues and technical challenges. In mid-May safety concerns led the U.S. Food and Drug Administration to put on hold a bid by Geron Corporation in Menlo Park, Calif., to conduct trials on patients who have acute spinal cord injury.

Now the 64-year-old Wilmut is one of several high-profile scientists who remain loyal to SCNT in concept but are leading a wholesale charge out of the field and into an alternative technology. That other approach, first demonstrated in 2006 by Shinya Yamanaka of Kyoto University, restores adult cells back to an embryonic-like state called pluripotency, in which they regain the ability to develop into any kind of cell. Any well-appointed lab can apply the comparatively straightforward technique. "It's really easy—a high school lab can do it," says Mahendra Rao, who heads up the stem cell and regenerative medicine business at Invitrogen, a life sciences corporation based in Carlsbad, Calif. Yamanaka's approach also enables scientists to leap over nuclear transfer's egg supply problems and sidestep qualms about destroying human embryos.

IAN WILMUT

SHIFT CHANGE: A pioneer in somatic cell nuclear transfer (SCNT), or cloning—a way to create embryonic stem cells—he now focuses on induced pluripotent stem cells (iPS cells).

HYBRID SOLUTION: To get around the egg-supply problem, Wilmut proposed inserting human DNA into animal oocytes. Recently approved in England, such chimeric unions have fueled political debate in the U.S. and hampered SCNT work.

Such practicalities, rather than a lack of inherent scientific value, seem to be driving the SCNT exodus. Wilmut describes his own switch in approach as a by-product of time-consuming responsibilities at the helm of the Scottish Center for Regenerative Medicine in Edinburgh, a post he assumed last year after nearly three decades at the nearby Roslin Institute. With 20 principal investigators demanding his attention, Wilmut's research on amyotrophic lateral sclerosis (ALS) had slowed to a crawl. "We thought it would be more likely that things could be made to happen quickly," he says.

Somatic cell nuclear transfer demands enormous skill and expensive equipment.

JEFF J. MITCHELL *Reuters/Corbis*

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It is easy to damage the unfertilized egg and hard to get the donated nucleus to operate in concert with its new host. Last fall Oregon Health & Science University researchers announced the first-ever success in primates—but the team went through 304 eggs from 14 rhesus macaque females to generate just two cell lines. And one of those had an abnormal Y chromosome. In humans the ability to collect fresh oocytes also remains a huge roadblock, especially because scientists cannot legally pay donors.

Yamanaka's ability to convert adult mouse cells into embryoniclike stem cells—called induced pluripotent stem cells (iPS cells)—has pumped fresh excitement into regenerative medicine. In this process, scientists use viruses to deliver three to four genes into an adult cell and to reprogram it back to its unspecialized state, enabling it to grow into any type of cell in the body. In a span of months, Yamanaka's team and three others reported success using human cells from adult skin and joint tissue and newborn foreskin.

Now it's hard to find a lab concentrating solely on embryonic cloning. Jamie Thomson, the first to pluck viable cells from a human embryo and grow them in culture, for instance, recently took charge of an institute focusing primarily on iPS cells. Although the technique is inefficient so far—less than 1 percent of cells become pluripotent—scientists see the iPS approach as a speedier path to cells suitable for disease research and, ultimately, the clinic.

With iPS, Wilmut enthuses, his team can study cell lines instead of wrestling to get them. "All you have to do is take some skin cells from somebody who apparently has inherited the disease, scatter some 'magic dust' on them and wait for three weeks," he says. "And you've got pluripotent cells." Wilmut and his collaborators, including George Daley of Children's Hospital Boston and Chris Shaw of King's College London, hope to use iPS cells to pinpoint mutations involved in ALS.

The method still does not promise quick cures. In ALS, for instance, researchers must speed up disease development and co-culture the various cells involved in the condition. Scientists would like to avoid retroviral vectors, risky because they deliver the genes randomly into the chromosome. Moreover, the new genes might vary in activity level, turn on in surprising ways or negatively influence other genes. Some teams succeeded in making iPS cells without the tumor-producing gene that Yamanaka used, but they also found that, as a result, they ended up with many fewer iPS cells.

Scientists do not fully understand how iPS reprogramming works—the inserted genes might represent a core regulatory circuit, or they might activate other genes. It is also not clear whether the results subtly differ from embryonic stem cells. No one yet has grown the two and made a side-by-side comparison, and survival after transplantation remains an unknown for both.

The iPS cells may force biologists to throw out accepted ideas about what it means to be a differentiated cell, says Zwaka, whose lab is studying characteristics of embryonic stem cells. Perhaps, he suggests, it is not necessary to take an embryonic cell through every step of development to create a particular cell type. There may be a set of "master regulators" that would enable, say, a skin cell to become an adult neuron without passing through the embryonic state.

Despite leaping on the iPS bandwagon, Wilmut and other cloning pioneers insist that embryonic stem cell research should continue. SCNT has offered important lessons about basic biology and will continue to enable studies of cell programming and reprogramming outside the genome. Only embryonic cells can answer questions about fertility and very early human development. Scientists will also likely rely on SCNT to produce mammalian models of diseases such as cystic fibrosis and for agricultural applications such as producing human proteins in animal milk.

"It's simply too early to start putting one avenue over another," says Daley, who is also president of the International Society for Stem Cell Research. His lab is using both SCNT and iPS to understand pluripotency. Daley fears that public sentiment may turn against embryonic work and dash hopes that a new U.S. administration will open up opportunities to clone new cell lines for research.

GOOD-BYE, DOLLY: Ian Wilmut, who ushered in a new era by creating the world's most famous sheep in 1997, fully supports cloning research despite having left the field.

ROBERT WALLIS *Corbis*

Indeed, as scientists turn their attention elsewhere, opponents of embryonic cell research have seized on the moment to attack. "There is no valid reason for any human cloning" or embryo destruction, wrote Tony Perkins of the Family Research Council. It is hard to escape the sense that SCNT research is on the wane. The ethical barriers and short egg supply remain daunting. If iPS pans out, Wilmut predicts, nuclear transfer to produce cell lines may one day become a history lesson. ■

Sally Lehrman is based in the San Francisco Bay Area. A Q&A version of her interview with Wilmut is at **www.SciAm.com/aug2008**

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Warming *and* Cooling

By Mark Fischetti

As the costs of oil, natural gas and electricity to fuel conventional heating and cooling systems rise, homeowners are increasingly installing heat pumps. By extracting warmth and coolness from the outside air or ground, heat pumps can provide greater efficiency and lower cost over the long haul.

Two basic options predominate. In air-to-air designs, a unit outside the house relies on air as a source of heat or a place to dump heat. In ground-based designs, fluid in tubes laid in the ground provides the heat transfer. In each case, a refrigerant travels in pipes from outdoors to an inside unit, and a blower sends the resulting warmed or cooled air through ductwork into various rooms [*see illustrations*]. The systems are often likened to a reversible air conditioner that can stream cool air or exhaust warm air throughout the home. "When the season changes, you just flip a switch and the flow reverses," says Leo Udee, account manager at Alliant Energy in Madison, Wis.

Even though both systems require electricity, they can attain greater efficiency than conventional designs because instead of consuming fuel to generate warmth or coolness from scratch they exploit heat or cold already present in the outside air or ground. Air-to-air systems are most effective when outdoor air is above 32 to 35 degrees Fahrenheit, however, so they are prevalent in the milder regions of the U.S. A small conventional heater can be added in colder climates, but that drives up cost. Ground-based systems with tubes installed six to eight feet below grade are useful in wider areas because the temperature of the earth does not dip below freezing at that depth, although they generally cost more to install.

Heat pumps have been around since the 1950s and have become more competitive in recent years because "the motors and compressors have gotten more efficient and cost less to operate," says Randy Scott, vice president of product systems management at Trane in Tyler, Tex. "And the condensers and evaporators can transfer more heat even as they have become smaller."

Heat pumps still command only a modest proportion of the home heating and air-conditioning market. Even so, both styles are seeing strong growth, especially for retrofits. So many homes were built in the 1970s, 1980s and 1990s, Scott says: "Their systems are nearing the end of their lifetimes."

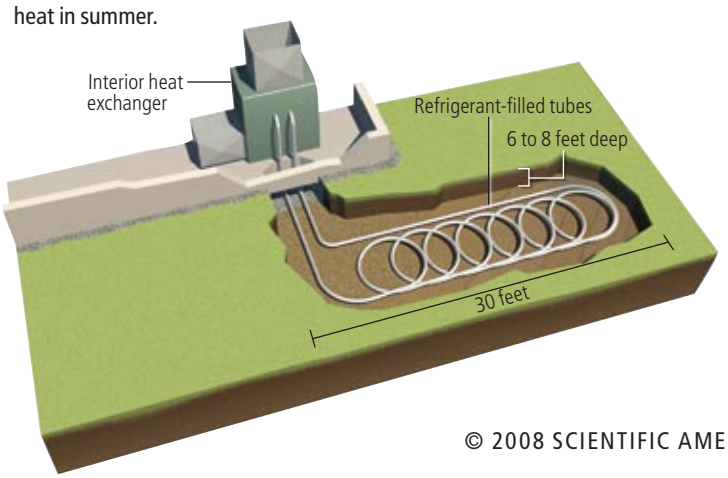
DID YOU KNOW ...

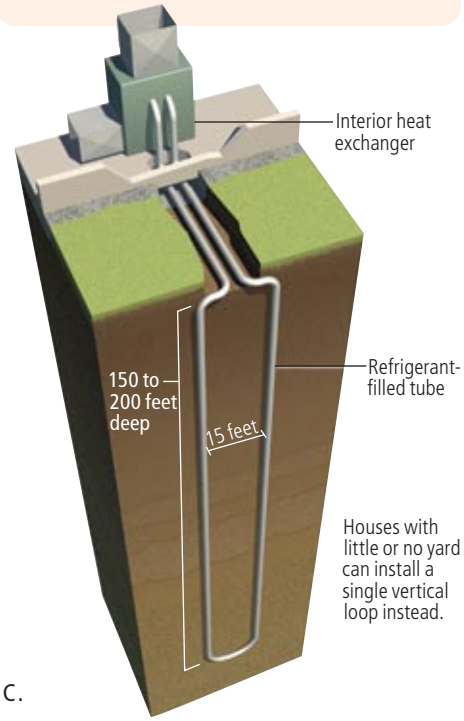
NO CHARGE? After a year of operation, as many as three quarters of residential heat pumps and central air conditioners may no longer hold the correct charge of refrigerant, which can reduce their energy efficiency by up to 15 percent. A service company can recharge the system, for a fee.

CHLORO-DELETED: Since the 1960s the most common refrigerant used in air conditioners and heat pumps has been a hydrochlorofluorocarbon known as HCFC-22, or, simply, R-22. But in the U.S. it will be banned in new products beginning in 2010 because it can release chlorine, which depletes ozone in the stratosphere. Manufacturers are replacing it primarily with a hydrofluorocarbon: HFC-410A.

WASTE FOR WATER: In summer, heat exchangers exhaust a lot of heat to the outdoors. Instead that warmth can be sent through an added pipe to an indoor water heater to create domestic hot water. In winter, the system does not generate enough waste heat, so conventional water heating is needed.

GROUND-BASED HEAT pumps work like an air-to-air unit (*opposite page*), but instead of warming or cooling a refrigerant with outdoor air they send the refrigerant underground, where it picks up heat in winter and dumps heat in summer.





GEORGE RETSECK

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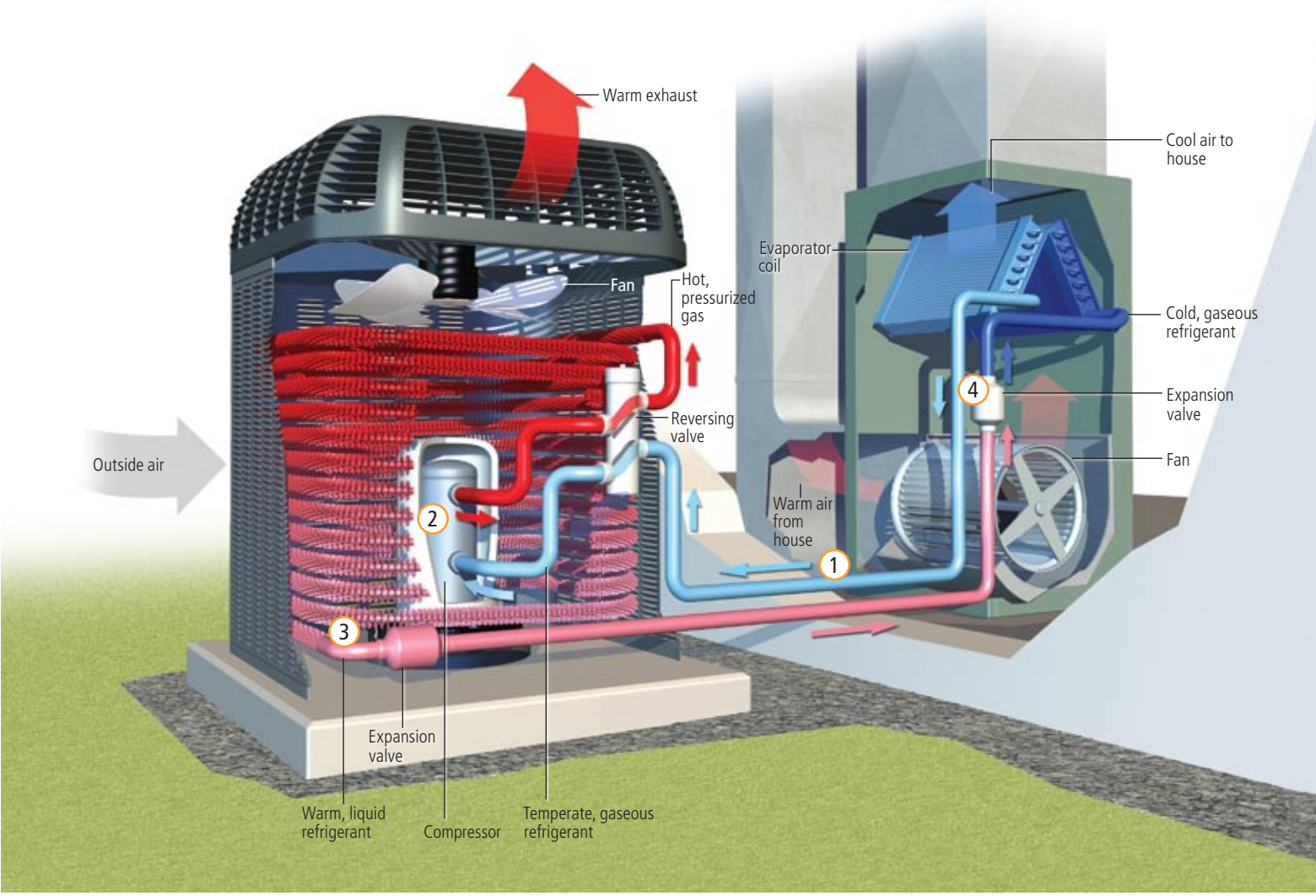
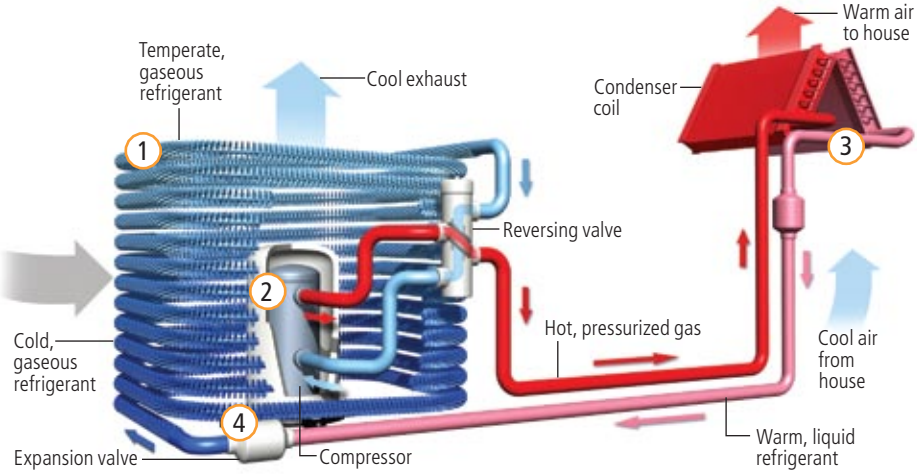
COOLING IN SUMMER

In air-to-air heat pumps, a temperate, gaseous refrigerant (*1*) from inside the house flows through a compressor (*2*), which compresses it into a hot gas. Outside air drawn across it whisks away heat, condensing it into a liquid (*3*). The liquid flows back into the house and through an expansion valve, which turns it into a cold gas (*4*). Fans blow warm air from inside the house across the gas inside an evaporator, cooling the air, which is sent back to the house. The warmed gas heads out to the compressor, and the cycle repeats.



HEATING IN WINTER

A temperate, gaseous refrigerant (*1*) in the outside unit flows through a compressor (*2*), which compresses it into a hot gas and sends it into the house unit. There cool indoor air blown across it picks up heat and is sent to warm the house. The refrigerant gas condenses into liquid (*3*) and flows back outside, where it passes through an expansion valve that turns it into a cold gas (*4*). As the refrigerant expands, it picks up heat from outdoor air, and it is sent to the compressor to repeat the cycle.



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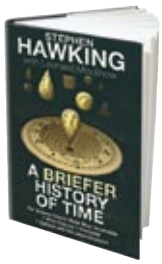
The Universe in a Nutshell ▪ Lost Tribes ▪ Science and Romance in China

BY MICHELLE PRESS

A BRIEFER HISTORY OF TIME

by Stephen Hawking, with Leonard Mlodinow. Bantam Trade Paperback, 2008 ($18)



"The title of this book," the authors write, "differs by only two letters from that of a book first published in 1988." That book was Stephen Hawking's *A Brief History of Time,* a publishing phenomenon that sold more than 10 million copies.

Despite its success, readers confessed to difficulty in grasping its more abstruse concepts. Hawking and Mlodinow (a physicist and writer) eliminated many of the technical explanations and clarified and expanded on the subjects of greatest interest—the creation of the universe, curved space, quantum gravity. They discuss developments during the past two decades in string theory and the discoveries of dark matter and dark energy. Clarity and conciseness do not have the almost mystical power of the original, but the book is a delight to read—and its new softcover makes it perfect for the proverbial summer day in the hammock.

JACOB'S LEGACY: A GENETIC VIEW OF JEWISH HISTORY

by David B. Goldstein. Yale University Press, 2008 ($26)

Goldstein, a geneticist at Duke University, combines jargon-free genetics with fascinating biblical history to probe the mysteries of 3,000 years of Jewish peregrinations. Is an

obscure South African Bantu group one of the lost tribes? Where did the remote Mountain Jews of Kurdistan and Dagestan come from? (Who even knew there were Mountain Jews?) Is the priestly lineage truly passed from father to son? To paraphrase the old ad for rye bread, you don't have to be Jewish to love this book. It is a specific—and gripping—example of how the lens of genetics will eventually inform our understanding of all peoples.

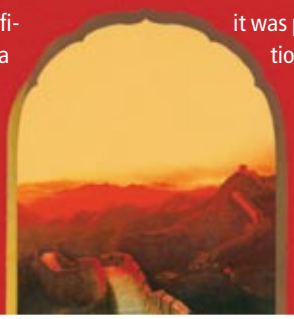
EXCERPT

THE MAN WHO LOVED CHINA: THE FANTASTIC STORY OF THE ECCENTRIC SCIENTIST WHO UNLOCKED THE MYSTERIES OF THE MIDDLE KINGDOM

by Simon Winchester. HarperCollins, 2008 ($27.95)

In 1943 a brilliant young biochemist arrived in war-torn China on a mission for the British government. Joseph Needham had become infatuated with China six years earlier, when he fell in love with a visiting Chinese student at the University of Cambridge. As Winchester (author of the best-selling The Professor and the Madman*) recounts, the enigmatic country and its little-known legacy of scientific innovation became Needham's lifework:*

"For Joseph Needham would assemble all his findings and their significance between the covers of a book—a book so immense in scale and so magisterial in authority that it stands today alongside the greatest of the world's great encyclopedias and dictionaries as a monument to the power of human understanding.



"The book, the first volume of which was published in 1954, and which had swollen to eighteen volumes by the time Needham died in 1995, continues to be produced today and now stands at twenty-four volumes, with 15,000 pages and 3 million words. It is called *Science and Civilisation in China,* and it is universally acknowledged to be the greatest work of explanation of the Middle Kingdom that has yet been created in western history. And all of it was planned and a huge proportion of it written by this bespectacled, owlish, fearless adventurer—a man who, since he was also a nudist, a wild dancer, an accordion player, and a chain-smoking churchgoer, was seen by some as decidedly *odd.*"

NOTABLE BOOKS FOR A DAY AT THE BEACH

1 **Thousand Mile Song: Whale Music in a Sea of Sound**
by David Rothenberg. Basic Books, 2008 ($27.50)
Rothenberg gives a comprehensive account of the scientific investigation of the songs whales sing. He is also a musician, and, using underwater speakers, he plays his clarinet for the whales, and they respond. You'll want to download the CD included with the book onto your iPod.

2 **The Backyard Birdsong Guide: Eastern and Central North America**
The Backyard Birdsong Guide: Western North America
by Donald Kroodsma. Chronicle Books, 2008 ($24.95 each)
You won't even need your iPod: these books include a built-in, touch-button electronic module that houses the vocalizations of 75 bird species.

3 **Peterson Field Guide to Birds of North America**
by Roger Tory Peterson. Houghton Mifflin, 2008 ($26)
For the more serious birder, an updated version of the classic in the field. It includes a Web site where readers can download video podcasts.

4 **Blasphemy**
by Douglas Preston. Forge Books, 2007 ($25.95)
Thriller fiction at the intersection of science and religion: supercomputers, supercolliders, black holes and the mystery of creation. It's great fun—especially after you have had the refresher course offered by Hawking and Mlodinow [*see above*].

FROM *THE MAN WHO LOVED CHINA* (*Great Wall*); FRED BUYLE *Realis Agence/Corbis* (*whale*)

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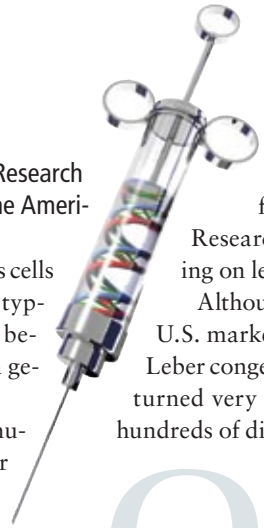
How does **gene therapy** work?



Arthur Nienhuis, a hematologist at St. Jude Children's Research Hospital in Memphis, Tenn., and outgoing president of the American Society of Gene Therapy, responds:

Gene therapy is the addition of new genes to a patient's cells to replace missing or malfunctioning genes. Researchers typically use a virus to carry the genetic cargo into cells, because that is what viruses evolved to do with their own genetic material.

Doctors can perform the treatment, first tested in humans in 1990, inside or outside the body. In the former case, they may inject the gene-carrying virus directly into the region that has defective cells. This approach is useful in therapies for Parkinson's disease, for instance, in which only part of the brain must be targeted.

Early in-the-body gene therapies used an adenovirus—the variety behind the common cold—but such an agent can trigger an immune reaction from the body. Today researchers use so-called adeno-associated virus, which is not known to cause any disease in humans.

In out-of-the-body gene therapy, researchers take blood or bone marrow from a patient and separate out immature cells. They add a gene to those cells and inject them into the bloodstream of the patient; the cells travel to the bone marrow, mature and multiply rapidly, eventually replacing the defective cells. Investigators are working on the ability to thus replace all of a patient's bone marrow or the entire blood system—as would be useful in treating sickle cell anemia, in which crescent-shaped red cells block blood flow.

Out-of-the-body gene therapy has already been used as a remedy for severe combined immunodeficiency (SCID), sometimes known as boy-in-the-bubble syndrome. SCID patients are unable to fight off routine infections and usually die in childhood. For this treatment, scientists use retroviruses, of which HIV is an example. These agents are extremely adept at inserting their genes into host cells' DNA. Some 30 children have been treated for SCID, and more than 90 percent have been cured—an improvement over the 50 percent chance of recovery offered by bone marrow transplants.

One risk associated with retroviruses is that they may stitch their genes anywhere into the host's DNA, disrupting other genes and causing leukemia. This complication has affected five of the SCID patients treated thus far; four of them, however, have beaten the cancer. Researchers are now working to lower the risk of bringing on leukemia.

Although no gene therapy products currently exist on the U.S. market, recent studies in both Parkinson's disease and Leber congenital amaurosis, a rare form of blindness, have returned very promising results. If this potential is borne out, hundreds of diseases could be eligible for treatment.

Why does **bread** go stale?

—H. Yang, Stafford, Tex.

James BeMiller, emeritus professor of food science at Purdue University, offers an answer:

Although the process has not been fully explained, the crystallization of starch polymer molecules is the most widely accepted, but not the only, contributing factor. Staling begins as soon as the loaf leaves the oven and begins to cool. How quickly bread hardens depends on its ingredients, how it was baked and its storage conditions.

Bread is a foamlike network made of starch molecules and molecules of a wheat flour protein called gluten. Inside this scaffolding are pockets of carbon dioxide gas produced by yeast during fermentation.

As time goes by, the starch molecules tend to crystallize. (Starch crystals are not like those of sugar or salt but are microcrystals formed in small regions of the starch polymer macromolecules.) Water is necessary for these crystallites to form, and the starch may take the required water molecules from the gluten. The removal of water from gluten changes it from a rubbery state to a rigid, so-called glassy state, firming the bread. Heating stale bread, however, will soften the glass, thereby freshening the bread. ■

HAVE A QUESTION?... *Send it to experts@SciAm.com or go to* **www.SciAm.com/asktheexperts**

LAGUNA DESIGN/PHOTO RESEARCHERS, INC. (*syringe*); DORLING KINDERSLEY *Getty Images* (*bread*)

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