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SCIENTIFIC AMERICAN

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MALARIA...WEST NILE VIRUS...HANTAVIRUS...DENGUE...CHOLERA...

Global Warming: The Hidden Health Risk

SCIENTIFIC AMERICAN
August 2000 Volume 283 www.sciam.com Number 2

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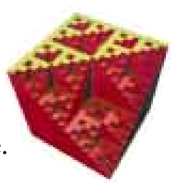

About the Cover

Painting by Roberto Osti.

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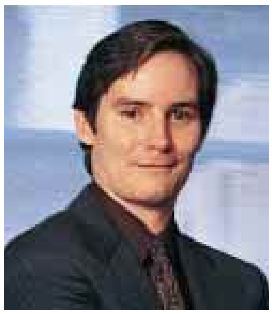
EDITOR_JOHN RENNIE

If You Can't Stand the Heat . . .

Global warming tends to inspire great huddles of pessimists and smaller gaggles of optimists. Happily, each faction can find grist for its mill in a new government report from the U.S. Global Change Research Program that projects how warming trends will affect this country. A draft of the report is being posted for commentary on-line at www.gcrio.org/NationalAssessment/ as this magazine goes to press.

According to the report's authors, climate models suggest that temperatures in the U.S. will rise on average five to 10 degrees Fahrenheit (three to six degrees Celsius) over the next 100 years—a larger increase than the rest of the world will generally see. The effects will vary from region to region: over much of the country, rainfall and humidity should increase, but the southeastern states might get hotter and drier. Flooding may be more widespread, but perversely, so too might drought, because water management grows more complex as winter snowpacks in the mountains recede.



ERICA LANSNER

Western deserts could give ground to shrublands. Some ecosystems, such as vulnerable coral reefs or alpine meadows, could disappear. Fortified by higher carbon dioxide levels in the atmosphere, forests might flourish, at least over the near term, but with a shifted mix of tree species. We humans, meanwhile, will probably contend with coastal flooding and other disruptions.

Pessimists and optimists can both find vindication in a new report on climate change.

Conversely, the new hothouse conditions could benefit agriculture. The government report is optimistic about the potential of farmers to adapt to changing climates and to raise crop productivity. For a world that depends so heavily on U.S. grains and other foods, this is good news. But the changes may not entirely be a boon for the farm belt: not all regions or crops would gain equal advantage, and farmers may suffer in an economic climate of more fierce competition and surplus. Nor does anyone yet know precisely how the pest populations could eventually cut into this boost in agricultural and natural productivity.

Scant discussion in the report goes to warming's effect on disease, which public health specialist Paul R. Epstein addresses in his article beginning on page 50. Tropical diseases such as malaria may become uncomfortably more familiar to those of us in the currently temperate zone. Although outbreaks such as New York's brushes with West Nile virus cannot be attributed to climate change, milder winters that help pathogens or their hosts survive make these events increasingly probable.

One of the best things to be said for the report is that it emphasizes how uncertain the course of global warming and its repercussions will be. Much depends on exactly how high and how quickly the temperature rises. Global warming's doubters like to emphasize the crudeness of even the best climate models, and they are right to do so. But the preponderance of evidence points to hotter days to come, which makes it only prudent to assess what the potential costs might be.

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Established 1845

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DON'T BEAM ME UP

With regard to "Quantum Teleportation," by Anton Zeilinger, I decided to put the processing requirements related to teleporting a 150-pound person into perspective, bearing in mind that teleporting a few grams (about 10^{24} atoms) would require processing 10^{24} bits of information. Obviously you would not want to use Ethernet for any part of the data-acquisition system, because even the emerging 10-gigabytes-per-second flavor would leave you waiting at least 22 billion seconds to materialize. What about a direct connection to a multiprocessing supercomputer? Even if you could get your data at 10 teraflops, you'd still be a random collection of atoms for about 22 million years.

You definitely would not want to be teleported without first making a copy of your data; 22 million years is kind of a long time to expect a computer to run without crashing. I'd want my data on DVD, but this would require 22 billion DVDs. Alternatively, you could live dangerously and store yourself in RAM. At $75 per 64 megabytes, however, it would cost you $1,000,883,789,062,500,000,000.99. Fortunately, the 22 million years you have to raise it means you would only have to invest about $5,000 at 20 percent—roughly comparable to a flight on the Concorde.

DOUG MORGAN
Irvine, Calif.

In the "Skeptics Corner" sidebar to the teleportation article, the author states that if each atom of iron in an automobile were exchanged with an atom of iron from a lump of ore, the *identity* of the car would be retained, being the same in all properties. My understanding based on the article, however, is that teleportation would produce an identical person but not the same person. The new creature might believe he was the same as the original, but the original would have ceased to exist. I think that this manifestation of myself would decline the opportunity for teleportation, no matter the benefit to the successor manifestation.

JOHN C. TOSHACH
via e-mail

Zeilinger replies:

Philosophers have discussed Toshach's question for more than 2,000 years. When is an object "identical to the original" and when is it "really the same"? Quantum physics teaches us that such distinctions only make sense if we can prove the difference by some observation or experiment. Therefore, because there is no way whatsoever to distinguish a perfectly teleported object from the original, it really is the same and not just identical.

SMART MICE

In "Building a Brainier Mouse," Joe Z. Tsien notes that mouse intelligence is limited by NMDA receptor properties but that these properties can be modified to increase memory, apparently without undesirable side effects. Although he explains why the ability to memorize decreases for older mice, Tsien does not address why natural selection has not further increased the time that the receptor is open (thus enhancing memory formation) for both juveniles and adults. Could such an enhancement lead to physiological side effects, or might the resulting higher intelligence lead to nonadaptive behavioral strategies? Such drawbacks would have fascinating implications for the development and administration of memory-boosting drugs.

ELLIOT NOMA
Metuchen, N.J.

JANA BRENNING (*digital illustration*); PHOTODISC (*maze*); CORBIS (*lamp*); PETER MURPHY (*mouse*)

SIDE EFFECTS for smart mice?

Tsien replies:

Levels of learning and memory are not solely determined by the opening duration of the NMDA receptors. It is highly likely that other molecules and different levels in complexity of neural network and circuits in the brain play a significant role in determining these mental capacities. The influx of calcium through the NMDA receptor is critical, but too much of it may cause brain cells to die. Evolution may have already selected for the receptors to stay open longer but only up to the point at which the organism becomes sexually mature and reproduces.

NONPROFIT CLINICAL TRIALS

In his excellent article "Understanding Clinical Trials," Justin A. Zivin focuses on drugs and medical procedures. But diet therapy and lifestyle changes can also treat certain conditions, with fewer side effects. To date, only a handful of dietary regimens have been tested rigorously, and most of these relate to heart disease. I am treating two ADHD children with diet therapy because, for them, this is more effective than drugs. Is this an anomaly, or does it represent a trend? If diet therapy helps even 3 percent of the millions of children on Ritalin, we need to establish

THE_MAIL

NO SOONER HAD THE APRIL ISSUE shipped than reader reactions to **"Quantum Teleportation,"** by Anton Zeilinger, began to materialize. Among the more imaginative responses were those proposing that only the neural structure of a person's brain need be transmitted to teleport a person—analogous perhaps to teleporting only the polarization state of a photon. Several people tried (futilely) to find ways to transmit information faster than the speed of light, for example, by using multiple entangled particles and error-checking codes within the content of the transmitted message. And commenting on the accompanying cartoon, **"The Quantum Adventures of Alice and Bob,"** an economist pointed out that the discovery of a vast supply of einsteinium crystals would depress the price of einsteinium, not raise it. He is correct—Bob should invest in www.einsteinium.com instead. Additional comments about this article and others in the April issue are featured above.

this fact and make it known to parents and physicians. Yet nobody is anxious to fund the relevant clinical trials because such treatments do not yield profits for investors. In fact, drug companies usually play devil's advocate because they don't want to lose any of their current customers. How can we, as a nation, determine the safety and efficacy of dietary and lifestyle changes when the corresponding studies are not profitable and cannot possibly be double blind?

KARL DAHLKE
Troy, Mich.

Zivin replies:

Pharmaceutical companies are businesses and have legal obligations to their shareholders to try to be profitable. They therefore have disincentives to evaluate therapies they cannot patent or that have very limited market potential. Patient advocacy groups and individual philanthropists have relatively limited resources, which they generally devote to basic investigation of disease processes. Only the government can be expected to fund the testing of treatments that are unlikely to be profitable. The National Institutes of Health, the primary source of medical research grants, devotes a sizable fraction of its allocations to such clinical trials. But among NIH administrators and their external scientific advisers, there are substantial differences of opinion concerning how best to distribute those resources. Additionally, political pressures and unrelated federal budgetary constraints can shape funding priorities. Diet and other lifestyle choices can be studied using clinical trial methodology in many instances, but such research is very expensive, and only government can be expected to support it.

Letters to the editors should be sent by e-mail to editors@sciam.com or by post to Scientific American, 415 Madison Ave., New York, NY 10017.

ERRATUM

In The Amateur Scientist [April], readers were advised to plug the heating rope into a ground fault switch (GFS) to help protect against electric shock. Good advice. But a GFS doesn't trip when the leads are shorted. Rather these devices disconnect a circuit if excess current flows to ground. Reader Leonard Herzmark, an engineer in Tucson, cited the National Electrical Code when he wrote to recommend that a three-prong plug be used to connect the thermos case to ground.

SCIENTIFIC AMERICAN

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50, 100 & 150 Years Ago

Zeppelin's First Flight, Observing a Firestorm

AUGUST 1950

WORLD FOOD—"The food problem confronts the world with two dangers. One is the political danger of hunger. A lifetime of malnutrition and hunger is the lot of two thirds of mankind. Yet in the midst of this dire need there remains the economic threat of the food surpluses generated by modern technologies. The abundant food output of the U.S. already has begun to undermine its prosperity. A World Food Board, as an agency of the U.N., would be responsible for maintenance of stable world prices, and would arrange for disposal of surpluses.—John Boyd-Orr, winner of the Nobel Peace Prize in 1949" [*Editors' note: The World Food Board was never created.*]

ULTRASONIC NAVIGATION—"Photographs of the wave-form of bats' ultrasonic sounds, as seen on the cathode-ray oscilloscope, show that a typical ultrasonic cry lasts only for about one five-hundredth of a second. An audible sound of this extreme brevity is heard as a sharp click. The frequency always seems to drop at least an octave from the beginning to the end of the pulse. Observations show that bats can use pulses of ultrasonic sound to detect objects as close as six inches. Under these conditions an echo will return to the bat's ears before the pulse can finish leaving its mouth. It would seem easier for a bat to distinguish between echo and original pulse if the two differed in frequency, as they do."

BLUE MONDAY—"In a study on employee morale in a British factory, two sociologists at England's University of Birmingham report: 'Morale is lowest on Mondays; attendance improves as pay-day and the week-end approach.' On comparing men and women in the factory, the investigators made a surprising finding: Monday absence was less marked for women. Their tentative explanation: 'Women do not mind so much going back to the factory on Monday, since the week-end does not bring them true leisure.'"

AUGUST 1900

ZEPPELIN'S AIRSHIP—"July second will long be remembered by aeronauts, for the first ascension of the great airship just completed by Count Zeppelin, the cavalry officer of Wurtemberg. On Lake Constance the last rope was cut at three minutes after eight and the airship began to move, trying to rise in a graceful curve. It attained a height of something over 1,300 feet and covered a distance of three and a half miles. One thing is very certain, and that is that no airship of the Zeppelin type will ever carry many people. The enormous expense incurred in building such airships would be a serious obstacle."

STAGE EFFECTS—"For years the public has been demanding more and more realism in plays. We present an illustration from a scene of 'Ben Hur' as played at the Broadway Theater, New York. The scene is the famous chariot race at Antioch, where Messala is thrown, causing him to lose the race. The chariot wheels do not rest upon the floor of the stage, but are actuated by a small electrically driven motor inside the body. The chariot of Messala is arranged so that at the critical moment when Ben Hur's chariot strikes it, powerful springs on the axle throw the wheels off and the body drops upon a yoke which is provided with springs."

TRICK CHARIOT on stage in *Ben Hur*, 1900

SEPTICWEAR—"The streets of our great cities can not be kept scrupulously clean until automobiles have entirely replaced horse-drawn vehicles. At the present time women sweep through the streets with their skirts and bring with them, wherever they go, the abominable filth which is by courtesy called 'dust.' The management of a long gown is a difficult matter. Fortunately, the short skirt is coming into fashion, and the medical journals especially commend the sensible walking gown."

CRAVING ICE—"The ice habit is making rapid progress in Great Britain, due largely to the incessant clamor for ice in hotels and public places by the thousands of traveling Americans. Consumption would increase if regular companies distributed it, but the business is in the hands of the fishmongers. Much of the ice is imported from Norway and a considerable quantity is manufactured."

AUGUST 1850

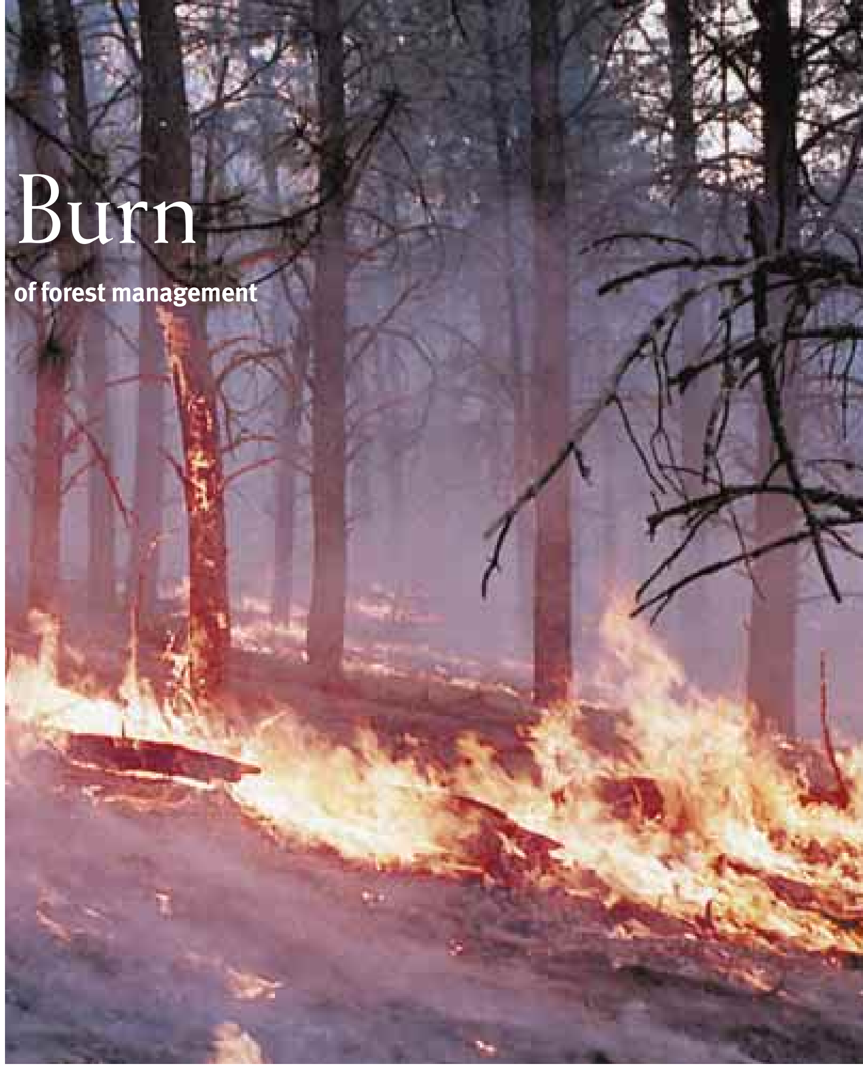
FIRESTORM—"A correspondent of the Philadelphia Ledger corroborates the theory of Prof. Espy, that a very large fire will, by a rapid rarefaction of atmosphere, cause an upward current, which must necessarily draw in from the surrounding atmosphere near the surface. He says of the recent large fire in Philadelphia: 'Until 9 o'clock, the strong southeast wind carried flakes of fire to neighboring buildings, and it appeared as though all the northern part of the city must be destroyed. At half-past ten o'clock I noticed the sparks ascending more perpendicularly and to a greater height, many assuming a spiral motion; I immediately made a circuit of the fire, and found the wind blowing strongly in from every side." [*Editors' note: The term for this effect, "firestorm," was coined in 1945.*]

FROM SCIENTIFIC AMERICAN

ECOLOGY_FOREST FIRES

Uncontrolled Burn

The Los Alamos blaze exposes the missing science of forest management



RAGING FIRE near Los Alamos, which lasted almost three weeks, has kindled debate about the role of logging, selective cutting and prescribed burns in the maintenance of healthy forests.

ELLIS NEEL *AP Photo*

The Cerro Grande fire in New Mexico was stunningly damaging for a prescribed burn. It raged for more than two weeks, consuming some 50,000 acres of national forest and land on and around Los Alamos National Laboratory. It destroyed 230 or so homes, displaced thousands of people, came perilously close to hazardous-materials sites on the nuclear-weapons research facility, scorched precious habitat for the threatened Jemez Mountains salamander and, some have speculated, may have played a role in the mysterious movements of Los Alamos hard drives containing classified material. And the danger posed by the fire has not subsided with the flames. Not only is the lab still vulnerable to ignition because of adjacent unburned forests, but the land is littered with plutonium and other dangerous waste that may be dispersed into the environment if the heavy seasonal rains cause mud slides and flooding.

Yet the blaze may have some positive effects. Perhaps most notably, it has renewed needed discussion about several challenges facing the federal agencies that manage land: the poor health of the national forests, the lack of man power and expertise needed to start and extinguish fires, and the paucity of research on the relative benefit or appropriateness of various approaches—logging, mechanical thinning and controlled burns—to restoring the forests. It has done so at a significant political juncture. Two proposals are now before Congress: one that would ban logging in national forests and one from the Clinton administration urging an end to construction of new roads on those same lands. Both policies, if enacted, could have important consequences for the use of fire in land management.

The Cerro Grande fire made the nation acutely aware of something that has been frighteningly clear to foresters and fire experts: what happened in New Mexico could happen almost anywhere, at any time. Many forests are so filled with fuel—deadwood and saplings resulting from more than a century of logging, grazing (which eliminated grasses that compete with trees) and a long-standing policy of fire suppression—that they are poised to ignite and burn uncontrollably and fiercely. The wildfires that have also raged this year in Colorado, Arizona and other parts of New Mexico are further evidence of this condition. “Everyone is pointing at the fact that Cerro Grande was deliberately set, but that could have easily been a lightning strike,” notes Martin E. Alexander of the Canadian Forest Service. “They were burning to prevent the very thing that happened.”

The fire that National Park Service employees ignited in Bandelier National Monument on May 4—and that became a wildfire sweeping toward Los Alamos on May 5—was one of about 3,000 set by federal agencies so far this year. Intentional burns started in the late 1960s, when the government began to recognize that the last half-century of fire quelling was adversely affecting forests, allowing exotic species to take hold and preventing fire-adapted species from thriving. The buildup of fuel was causing flames to burn more intensely, killing off the older trees that typically survive fire and are the key to forest regeneration. As W. Wallace Covington of Northern Arizona University notes, destructive crown fires—those that move through the forest as a sheet of flame instead of hugging the ground—have increased exponentially. Between 1931 and 1950, crown fires burned 12,000 acres in the Southwest; between 1991 and 1997, they consumed 331,000 acres.

The death of 34 firefighters in catastrophic fires in 1994 reinforced the notion that fuel reduction was imperative. And in 1998, after new appropriations and an organizational revision of federal fire-management policy, Secretary of the Interior Bruce Babbitt called for a threefold increase in the number of burns set. Although that precise goal has not been reached, the amount of burned land has grown enormously: from 918,300 acres in 1995 to 2,240,105 in 1999. Less than 1 percent of those fires get out of hand, according to the National Interagency Fire Center: only 257 of the 31,212 fires set by the various federal agencies in the past five years. (Even those few fires can be lethal, however. As Stephen J. Pyne of Arizona State University points out, some of the most deadly fires of the past 20 years were prescribed burns gone awry.)

Despite the widely recognized need to rejuvenate the forests and to forestall an increase in deadly fires, the solution is hotly contested. The logging industry argues that thinning the forests can reduce the threat of fire. "As devastating as Los Alamos was, it was minor," says Derek Jumper of the American Forest and Paper Association, which advocates increased logging. "Our public lands are facing the worst health crisis they have ever faced." Many environmentalists beg to differ. They worry that thinning, or "salvage," just opens the door to full-scale logging, because companies can't make a profit unless they take out the larger trees and because uses for the smaller trees—particleboard or utility poles, for example—may not counterbalance the cost of removal. And neither side trusts the Forest Service's judgment. "There is a lot of Old Testament on all sides: an eye for an eye," Covington explains. "They want to fight and win at all costs."

Some experts, including Covington, are calling for a middle road in the debate: a more nuanced approach that would allow logging, when appropriate, or thinning or burning—or all three, depending on the needs of the forest. Unfortunately, the science that could provide such guidance is lacking. There are very few long-term studies on the effects of fire applied over time to different ecosystems, says Ronald Myers, director of fire management at the Nature Conservancy. Several reports—conducted by the General Accounting Office and the Congressional Research Service, as well as by the Department of the Interior and the Department of Agriculture, which runs the Forest Service—have noted that there are virtually no data on how various treatments mimic the ecological functions of fire. "Four or five studies have indicated increased fire intensity in the wake of logging," summarizes Niel Lawrence of the Natural Resources Defense Council. "And one study picked two plots nonrandomly and did show a reduction."

Despite decades of controlled burning, studies that may help managers figure out when and where and if to log or burn are just getting under way. C. Phillip Weatherspoon and Carl N. Skinner of the Forest Service, for instance, are beginning a comparative study of fire and fire surrogates on coniferous forest in California. "I think what is noteworthy is that this is a serious and ambitious study," Lawrence says, "and that the scientists are candid about the lack of empirical information."

Other researchers, Covington and his colleagues among them, are also investigating as many variables as possible, trying to balance fire, thinning, judicious logging and perhaps even the use of horses to remove fuel from roadless lands. As for the Cerro Grande blaze, it will need to be studied as well. Covington worries that the crown fire was atypical for the ponderosa-pine forests and other habitats and that they may not come back. But it will be a while before the country has any clear procedures that would rejuvenate forests while avoiding millions in damage. "Fire ecology is a really tough field," Pyne says. "All fires are different. It is not like the lab, where you turn on the burner. It just boggles the mind." *—Marguerite Holloway*

CONSERVATION_BIODIVERSITY

Island Survivors

On what once was a North American Galápagos, researchers try to save devastated wildlife

GUADALUPE ISLAND, MEXICO—"Vermin. Rats with horns. Evil," Jon P. Rebman tells me as we hike across this rugged volcanic island about 150 miles west of Mexico's Baja California peninsula. "I could keep going. They've really eaten nearly everything."

Rebman, curator of botany at the San Diego Natural History Museum, is referring to the some 10,000 goats that have transformed the lush forest of Guadalupe Island into a barren field since they were introduced by sailors some 150 years ago. Now he and his colleagues are searching for the few remaining endemic plants that may have escaped the marauding herd.

We enter a steep canyon that once was shaded by groves of pine, palm and oak trees but is now stripped except for a few sickly palm clumps on each side. Struggling ferns line the inside canyon walls, along with piles of goat waste and bleached goat bones.

Along with Thomas Oberbauer, a botanist from the San Diego Planning Department, and José Delgadillo of Universidad Autónoma de Baja California in Ensenada, Rebman digs plants out of crevasses and scales cliffs to snip out-of-reach shrubs. They find one honeysuckle plant that may never have been seen before on the island, but that's about it.

LOOKING FOR NESTING SEABIRDS is ornithologist Robert Pitman of the Southwest Fisheries Science Center in La Jolla, Calif., on a small islet just off Guadalupe Island.

PHOTOGRAPHS BY JEFFREY BROWN *Aurora*

Guadalupe Island once was home to more unique plants than any other island on North America's Pacific Coast: 34, a count that rivaled the biological diversity of the Galápagos Islands. But since the goats arrived, 26 of the island's 156 native plants have gone extinct, including six found nowhere else in the world. Half of the island's pine trees have disappeared since the late 1960s, unable to reproduce because goats eat the seedlings. A cypress forest located 4,300 feet along the island's central spine of mountains is turning into a wasteland of eroded soil, rocks and dead trees, according to Philip Unitt, an ornithologist at the San Diego museum. "It's 95 percent of the way to Mars," Unitt says after spending his fourth day camped among the cypress trees. "The whole ecosystem is dysfunction-

GUADALUPE'S GOAT-FREE ISLETS (*left*) to the south contain rare plants that may eventually be transplanted to the main island, which, thanks to 150 years of grazing by goats (*below*), has been rendered mostly barren (*bottom*).

al. I knew things were bad, but I wasn't prepared for the reality of what it really was."

Our campsite in the pine forest rests atop a 3,000-foot-high ridgeline, affording us dramatic views of the coastline directly below, as well as examples of how the island has changed. Exotic earwigs—tiny insects with pincers on their tails—infest sleeping bags, boots and food supplies. Sparse, weedy grasses provide little comfort on the sharp lava rocks, and much of the soil is gone. These creatures, along with European starlings and mockingbirds, are becoming the new rulers of Guadalupe's wildlife kingdom. They are displacing less adaptable native creatures, such as the purple-flowered, sausagelike succulent shrub *Cistanthe guadalupensis,* which survives only on three smaller islets, and the Guadalupe storm petrel, one of five birds endemic to the island that have vanished in the past century. The only native creature doing well is the Guadalupe fur seal, which now numbers more than 5,000. The seal was declared extinct in the early 1920s, but its population has increased 13 percent a year since the late 1950s, when its hunting was banned.

Seventeen U.S. and Mexican biologists sailed to the island in June to collect plants, birds and insects while documenting damage from the vacuum cleaner–like herbivores, which were left by Russian whalers and fur-sealers looking to establish a reliable food source. Scientists have been collecting the island's flora and fauna since Smithsonian botanist Edward Palmer was marooned here for four months in 1875—and became sick from eating too much goat meat. (He managed, however, to bring home 1,200 plant specimens.) But this expedition is the first to use a helicopter, all-terrain vehicles and satellite phones to put researchers into inaccessible places.

One such location is a small islet off Guadalupe's southern tip, whose 400-foot-high cliffs have never been scaled by humans. On a rolling 25-acre meadow atop Islote Adentro, or Inner Islet, we find a trove of native plants—relatives of the poppy, buckwheat, wallflower, morning glory and tar plant—that once covered the entire main island. Because they evolved apart from grazing animals, the plants never developed spines, foul-tasting leaves or other natural defenses and thus were easy pluckings for the goats.

The expedition's organizers believe the way to save Guadalupe Island's ecosystem is to remove the goats as quickly as possible. That would give the island's native vegetation a chance to recover and perhaps bring back some of the birds that depend on it.

William T. Everett, president of the Endangered Species Recovery Council and one of the leaders of this expedition, says special goat-sniper teams, rather than your average hunter, would do the job from helicopters. When the population was cut down to size, researchers might then deploy a "Judas goat," a radio-collared female goat in heat, to act as bait to attract the remaining males. Everett notes that goats are extremely prolific breeders, and even two or three survivors could make the entire eradication program worthless. "The only goat that really matters is the last one," he explains. "Particularly if it's a female."

Proponents point to the goat removal program at San Clemente Island, a military reservation about 100 miles west of San Diego, as proof that such a strategy could work. Although it took 20 years of court battles against animal-rights advocates, state and federal conservation officials were finally able to declare San Clemente goat-free in 1994. Since then, native trees and plants have made a comeback, as have some of the island's other native fauna. In the coming months, the expedition members will assemble a proposal to the Mexican government detailing their findings and offering a plan to remove the goats. Perhaps the goats' only supporter is the Mexican navy, which operates a small garrison on the southern end of the island and sells the rights to export 1,000 live goats a year to a goat breeder based in Sonora, Mexico.

Exequiel Ezcurra, the museum's research director and a former head of the Mexican National Institute of Ecology (equivalent to the U.S. Fish and Wildlife Service), explored the island for the first time on this expedition. He says that a proposal written by Mexican and U.S. scientists has a good chance of gaining support from the Mexican government, despite the navy's opposition. "There is a window of opportunity that did not exist several years ago," Ezcurra remarks. "It's just a question of convincing the right authority in government."

Even the small community of lobster and abalone fishermen on the island realizes the long-term problem of the goats. Although they enjoy an occasional goat barbecue, they have seen much of the plant life around their village disappear. Even worse, their only source of freshwater is a spring that is formed by fog water collected by the cypress forest. As the trees disappear because of goat grazing, so does the water. "It's a good idea to remove the goats," said Raoul Urrias, leader of Guadalupe's fishing cooperative. "We have to take care of the forest."

—Eric Niiler

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

MICROSCOPY_CELL DEVELOPMENT

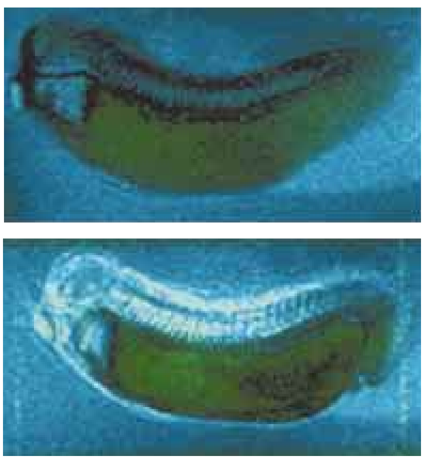
Gene Scenes

New magnetic resonance imaging lights up cells when their DNA turns on

CLEVELAND—Imagine that you are an alien commissioned to decipher a football game. Equipped with nothing more than a Polaroid camera and a truckload of film, could you accurately explain the sporting event given that, to your otherworldly sensibilities, the halftime show carries just as much importance as the kickoff? That scenario depicts the challenge facing researchers who track cells during the development of embryos and tumors. Outfitted with scalpels and microscopes, investigators must try to explain the workings of biology by killing embryos or removing tissue samples, fixing them on slides and piecing together the "snapshots" taken over time. And there is no way to tell what is meaningful to the game and what is halftime fluff.

Chemist Thomas J. Meade and his colleagues at the California Institute of Technology may have found the engineering equivalent of a video camera and an on-field microphone. This past May at a National Academy of Engineering meeting in Cleveland, Meade unrolled stunning videos of frog embryos unfolding from egg to tadpole stages. With unprecedented detail and cellular-level resolution, the images showed the creatures' cells at work communicating with one another during development.

The three-dimensional shots came from magnetic resonance imaging (MRI), which detects vibrations in the hydrogen atoms of water that are induced by an intense magnetic field. To enhance contrast, researchers add an element, such as gadolinium, that speeds and amplifies hydrogen's signal emission. But typical contrast agents report only the topography of soft tissue. They cannot, for instance, distinguish between dead tumor tissue and robust, newly developing cancers nor track specific cells—and their daughter cells—in a developing embryo. In a way, MRIs give anatomical information akin to a video camera projecting pictures without sound.



DEVELOPING FROG EMBRYO glows when a particular gene is activated.

THOMAS J. MEADE *California Institute of Technology*

To add the audio, Meade employed a novel contrast agent that lights up specific cells as their genes turn on. Meade started by fashioning a molecular basket for each gadolinium ion out of clawlike molecules called chelators, and he latched the basket shut with a sugar called galactopyranose. The only way to lift the lid was through an enzyme that chewed up the sugar specifically. In the first experiments, Meade's graduate student Angelique Y. Louie injected the caged gadolinium into both cells of a two-celled frog embryo and then injected one of those cells with the gene for a lid-digesting enzyme. Real-time MRI then produced a video of the developing embryo with half its cells lit up as the gene turned on, encoded the enzyme and permanently lifted the lids of the gadolinium cages. The exposed metal interacted with the water and shot off a bright signal.

"This is the platform for a whole slew of enzymatic processes," says Meade, who first reported the work in the March *Nature Biotechnology*. Indeed, by changing the latch so that it becomes the substrate for any enzyme—for example, one produced only by live cancer cells or by cells that spur new blood vessel growth—the technique can be tweaked to monitor tumor growth or to track the fate of any number of cells and their contents down to 10 microns in size. Figuring out ways to provide such functional information "is one of the most interesting areas in magnetic resonance imaging now," comments biomedical engineer David L. Wilson of Case Western Reserve University.

At the meeting, Meade presented his team's progress in chemically weaving a gadolinium basket that opens and shuts based on intrinsic calcium levels. Such a basket could track, in fine detail, brain or nerve activity, both of which involve sending impulses via calcium fluctuations. Other ongoing projects include hooking up drugs to the basket handles that are activated when a normal cell enzyme clips them off. That would be a breakthrough in the local delivery and detection of chemotherapy agents at a tumor site, for example, because it would distinguish between dead tissue and live cells. "Now," Meade says, "we have a powerful toolbox." *—Trisha Gura*

TRISHA GURA is a freelance science writer based in Cleveland.

ASTRONOMY_INTERGALACTIC SPACE

Magnetic Anomalies

What are magnetic fields doing in the middle of nowhere?

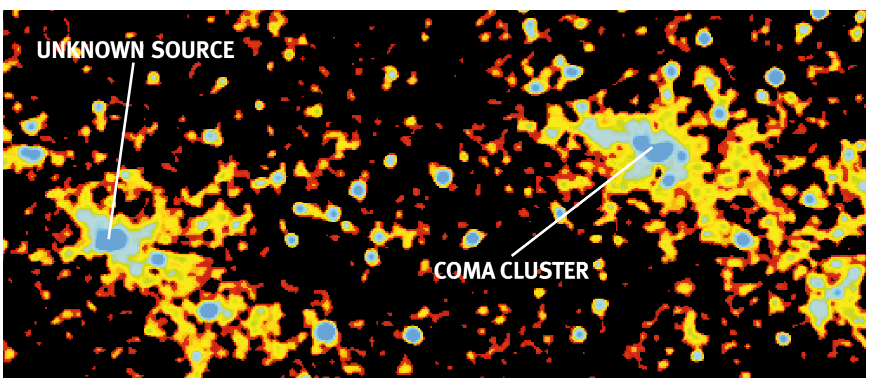
The next time you visit deep space, don't forget to pack a compass. It might not be much use for navigation, but it will be one of the few ways you can take in one of space's sublimities, the magnetic fields. The lines of magnetic force twist and wind through the interstellar miasma and arch over millions of light-years of intergalactic wilderness. They are, astronomers have gradually realized, one of the great shaping forces of the universe. Now it seems that even the outermost of outer space—the chasms between clusters of galaxies—is pervaded by magnetic fields of unforeseen power and unknown origin. "These magnetic fields are the dominant free energy of the universe," says astrophysicist Stirling A. Colgate of Los Alamos National Laboratory.

Magnetism had long been considered a side attraction in astronomy—hard to measure, hard to master, seemingly easy to neglect. The basic trouble is that the fields are invisible. To infer their presence, astronomers must make do with such compasses and filings as nature has haphazardly provided, including dust grains and charged particles. By aligning dust grains or diverting the paths of electrons, for example, a magnetic field can effect the emission of polarized radio waves or skew the polarization of light passing through a region of space, rather like a weak pair of polarizing sunglasses.

Gradually astronomers have deduced that the Milky Way has a magnetic field of roughly five microgauss, generally directed along the galaxy's spiral arms. (By comparison, the earth's north-pointing magnetic field is about 500,000 microgauss.) If you had a compass sensitive to this field, in our corner of the galaxy it would point toward the constellation Cygnus. Other galaxies have similar fields.

When researchers began to look for fields in between galaxies in the late 1980s, their expectations were low. After all, cosmic magnetic fields are embedded in plasmas, which are much thinner in intergalactic than in interstellar space. According to x-ray telescopes, even the thickest intergalactic plasmas—found in the cores of galaxy clusters—are a hundredth as dense as interstellar plasmas. So it came as a surprise in 1990 when Philipp P. Kronberg and Kwang-Tae Kim, both then at the University of Toronto, announced the first magnetic readings of the interstices of the Coma cluster. The cluster's field is nearly as strong as the Milky Way's.

Puzzled theorists took refuge in the thought that Coma was a fluke. But that escape hatch slammed shut when Kronberg, Tracy Clarke of Toronto and Hans Böhringer of the Max Planck Institute for Extraterrestrial Physics in Garching, Germany, reported their latest findings at a meeting of the American Physical Society this past April. The 24 other clusters they probed all have galactic-strength fields, too. Such fields are as potent as other cosmic forces, so they can no longer be ignored in models of galaxy formation and other celestial goings-on.



VERY ATTRACTIVE: **Magnetic fields suffuse the space in and around the Coma cluster of galaxies. The fields are traced out by 74-megahertz radio emissions (*blue is strongest, red weakest*) from the cluster, unrelated galaxies and unknown sources.**

PHILIPP P. KRONBERG *University of Toronto*, TORSTEN E. ENSSLIN *Max Planck Institute for Astrophysics*, RICK A. PERLEY *National Radio Astronomy Observatory* AND NAMIR E. KASSIM *Naval Research Laboratory*

Kronberg also unveiled new measurements of the space beyond clusters of galaxies, made with a special low-frequency radio receiver installed two years ago on the Very Large Array telescope in Socorro, N.M. Kronberg and the rest of his team—Torsten A. Ensslin of the Max Planck Institute for Astrophysics in Garching, Richard A. Perley of the National Radio Astronomy Observatory and Namir E. Kassim of the Naval Research Laboratory—found that magnetic fields just outside the Coma cluster are 0.01 to 0.1 microgauss, also too strong for many theorists' comfort.

Explaining cosmic magnetism has never been easy, and now the task is even more daunting. A galactic field must somehow be generated from scratch, amplified to the strength now observed, ejected into intergalactic space and further amplified there. Each stage poses problems. And some worry that ordinary galaxies simply lack the oomph to magnetize the huge space between them. Colgate and his colleague Hui Li think it is a job for the biggest guns in astronomy, the black holes at the heart of so-called active galaxies. "The only place where you have that much energy is a supermassive black hole," Colgate says.

For all the questions they raise, the intergalactic fields might resolve a separate mystery: the origin of ultrahigh-energy cosmic rays. None of these superparticles has come from the direction of a plausible source, such as the nearby active galaxy M87. But, as Glennys Farrar of New York University and Tsvi Piran of Hebrew University of Jerusalem argued in *Physical Review Letters* in April, sufficiently strong intergalactic fields would deflect the particles' paths. If so, M87 can't be ruled out after all.

Alas, the proposal immediately ran into controversy. The Milky Way is not part of a cluster, and magnetic fields in its vicinity have yet to be measured. Arnon Dar of the Technion in Haifa, Israel, argued that the fields cannot have the requisite strength, as that scenario would contradict other observations. Kronberg thinks the same process that amplifies the intergalactic fields might also be responsible for the particles. In any event, it looks like cosmic magnetic fields will retain their lure for some time to come.

—George Musser

Global Positioning

New fossils revise the time when humans colonized the earth

Scientists have long known that hominids arose in Africa, and for the first few million years they stayed there. But at some point our ancestors began to move out of their motherland, marking the start of global colonization. Determining why and when they left, however, has proved difficult because of the scarcity of early human fossils. Now two ancient skulls from the Republic of Georgia provide the strongest evidence yet of the first humans to journey out of Africa. According to a report in the May 12 *Science,* they appear to have accomplished this far earlier—and with a much more modest technology—than many investigators had expected.

Researchers unearthed the skulls in Dmanisi, about 85 kilometers southwest of the Georgian capital, Tbilisi. Based on radiometric dating of the volcanic layer underlying the fossils, paleomagnetic measurements and the presence of animal species whose age has been documented elsewhere, the team dated the skulls to around 1.7 million years ago—at least 300,000 years older than stone tools from a site in Israel called ‘Ubeidiya that were considered the oldest undisputed traces of humans outside Africa.

HUMANS LEFT AFRICA EARLY, according to two new Georgian fossils, one of which is shown here (*inset*). Previous estimates based on ages of known fossils (*map*) had suggested a much later dispersal.

GOURAM TSIBAKHASHVILI, COURTESY OF DAVID LORDKIPANIDZE (*photograph*); LAURIE GRACE (*map*)

The finding—coupled with previously known fossils from Dmanisi whose antiquity was originally doubted—overturns a popular theory aimed at explaining what prompted the first colonizers to venture out of Africa. The stone tools from ‘Ubeidiya represent an advanced industry known as Acheulean, which includes carefully crafted hand axes and other double-edged tools well suited to carving meat. The earliest Acheulean tools come from Africa and date to about 1.6 million years ago. Prior to that, hominids were using a more primitive technology dubbed Oldowan. Researchers thus proposed that the development of the Acheulean enabled early humans to finally leave Africa, because the tools gave them a better means of scavenging and hunting. Dmanisi, however, has yielded Oldowan, not Acheulean, tools.

Taking that into consideration, a more viable explanation for the dispersal stems from anatomical shifts rather than new technology, according to team member David Lordkipanidze of the Georgia State Museum. The Dmanisi hominids most closely resemble an early member of our genus that some researchers call *Homo ergaster* (others prefer the designation early African *H. erectus,* and still others call it early *H. sapiens*). With the emergence of this form around two million years ago, says University of Michigan paleoanthropologist Milford H. Wolpoff, “we get someone who is three times the weight and twice the height of all australopithecines, with really long legs.” The only way to maintain this body size, he notes, is through a higher-quality diet than that of the australopithecines. Higher quality, in this case, probably meant including meat. With long legs, *Homo* was well equipped to patrol the larger home range that carnivory requires. After adopting this hunter-gatherer subsistence strategy, it was only a matter of time before these ancient humans expanded into Eurasia.

Indeed, researchers will most likely uncover Eurasian remains even older than Dmanisi, surmises Susan C. Antón, a paleoanthropologist at the University of Florida and member of the Dmanisi research team. Remains from Java hint at human occupation as early as 1.8 million years ago, and getting there would have required moving through Eurasia. Although many scholars regard the date assigned to these fossils with a great deal of skepticism, early *Homo* certainly could have reached Southeast Asia within that time frame, according to Harvard University archaeologist Ofer Bar-Yosef. In fact, he estimates that such a dispersal would have taken hunter-gatherers only a few thousand years. (Importantly, as with Dmanisi, the only tools known from the earliest East Asian sites are of the Oldowan variety.)

Early dates for Java aside, humans had reached eastern China by 1.1 million years ago. Yet the earliest accepted Europeans are 780,000-year-old fossils from Spain. Why they appear to have taken so long to reach western Europe, which is closer to the exit route from Africa than is East Asia, remains unclear. One theory posits that large-jawed carnivores, which left little for scavengers, prevented humans from establishing a foothold there. Others imagine that inhospitable climate and geography thwarted early European colonization. But Bar-Yosef suspects that older European sites will turn up, demonstrating that some of the emigrating groups headed from Africa into Mediterranean Europe. A more conservative view comes from Antón, who doubts that any older fossils will come from that region. Then again, she remarks, “Dmanisi really shows us how little we know about the potential sites that are out there.” —*Kate Wong*

PSYCHOLOGY_GROUP DYNAMICS

More Than the Best Medicine

Hear the one about the baboon with the wooden leg? Laughing to make friends and influence others

ITHACA, N.Y.—Psychologist Jo-Anne Bachorowski of Vanderbilt University has learned an important lesson from her research on laughter: "I know now to snort and grunt only with friends but never around men I want to impress." Bachorowski, her Vanderbilt colleague Moria Smoski and Michael J. Owren of Cornell University have tested how men and women respond to and use laughter. They have discovered that the quality of a laugh can make someone more or less attractive. More interesting, other people in the room affect how much, and in what form, someone laughs. Women laugh more wildly around male strangers, but men laugh most with their buddies. And these differences, the researchers suggest, make evolutionary sense.

In one experiment, subjects listened to recorded laughs and were asked to "rate" the sound: Would they like to meet the laugher? Unvoiced laughs—like that of your friend who opens his mouth, rocks back and forth, and pants like a hyena—failed to attract any interest. Snorters and grunters, especially women, were also not high on anybody's list. But the woman with the singsong laugh, well, she could have a date every night. Such women were rated as even friendlier and sexier than men with the same kind of laugh.

CHUCKLEFEST: A scene from *Monty Python and the Holy Grail* was used to determine how men and women laugh in particular social situations. Hint: to be attractive, avoid snorting.

To get at exactly how laughing influences a social situation, the investigators then asked the subjects, alone or paired with a friend or with a stranger, to watch film clips. Among them were the fake orgasm scene from *When Harry Met Sally* and the "Bring out your dead" skit from *Monty Python and the Holy Grail*. Who wouldn't laugh?

These people certainly did, but in unexpected ways. Women laughed more with male friends than with female friends. More interesting, their laughs were more highly pitched—that is, more extreme—when they were with a male they had never met. Alone or with other women, they were more subdued. The men, in contrast, laughed more, and more extremely, with their male friends.

Laughing obviously is not just an emotional reaction but also a social signal. Just what the signal is all about is unclear. "After all, there's no necessary reason to produce a laugh," comments Bachorowski, chuckling softly. Humans are the only creatures that laugh (stupid pet tricks aside). Clearly, other animals seem to feel happy—just watch two monkeys groom each other and see the body language of bliss—but they never laugh. Some, like chimpanzees, might smile occasionally, but it demonstrates submission and has nothing to do with feeling good or hearing a funny joke. Young chimps open their mouths and puff air when they play, and their behavior could be considered a precursor to human laughing. But it isn't close to the way humans of all ages laugh.

Owren and Bachorowski speculate that human laughter evolved as a unique way to make and break alliances. First came the smile, which must have communicated a positive emotional state to someone else; our ancient ancestors probably used those smiles to reassure one another and build alliances. But of course, smiles can be faked, and so what evolved as an honest signal was probably soon corrupted. Enter laughing, a much more complex signal. Laughing involves more neural systems, the use of vocal apparatus and lots of energy. "You have to be a much better actor to fake a laugh convincingly than fake a smile convincingly," Owren says. And so laughing probably replaced smiling at some point in human history as an honest signal in coalition building.

And the right laugh at the right time can even manipulate others. When the women in this study laughed more wildly with male strangers, they may have been unconsciously arousing the men. Not in a sexual way, but enough to make the guy feel positive. That's a good idea, because unfamiliar males pose a physical and sexual threat to women. "When women have men in this state—in a good mood and ever hopeful [for sex]—they are more malleable," Owren theorizes. In the same way, when the men in the experiment laughed the most with other men, they were probably honoring the age-old tradition of the buddy system, reinforcing those male bonds with a good guffaw.

To test their hypothesis further, the researchers are now looking at how laughing affects more complex social situations, such as game playing, and they hope to use medical imaging techniques to follow the path of laughter through the brain. Meanwhile remember this: the next time you laugh, avoid the snort and make a cheery noise, unless you're alone or want to be.

—Meredith F. Small

MEREDITH F. SMALL is a writer and a professor of anthropology at Cornell University. Her latest book is Our Babies, Ourselves: How Biology and Culture Shape the Way We Parent *(Dell, 1999).*

KOBAL COLLECTION/PYTHON PICTURES/EMI

GROWTH_POPULATION

The U.S. Population Race

In the standard demographic scheme, population change results from three forces: births, deaths and migration. In the period 1970–1999 the U.S. saw about 110 million births and 63 million deaths, a natural increase of 47 million. Domestic migration was far greater: there were 425 million occasions in which Americans moved to another county in the same state or to a different state altogether. (The more than 750 million occasions in which Americans moved within counties are not reflected in the map.) The 38 million who migrated to the U.S. from abroad had a small effect overall on the redistribution of population, except in a few areas such as New York City.

Technology and the economy, of course, largely govern regional migration. The long-term decline of population in the Buffalo and Pittsburgh regions traces mostly to the crisis in heavy manufacturing of the 1980s. Because other industries could not absorb the laid-off workers, many job seekers relocated, particularly the young. Those who stayed, being older, had fewer children. The demographic shock was so great that populations in these areas are still about 15 percent below 1970 levels.

Other regions suffered similar shocks in the 1980s yet recovered. The Minneapolis–St. Paul region, for example, successfully rebounded after its mainframe-computer business collapsed precipitously. Attracting new industry has long been the goal of municipal boosters, but the Minneapolis–St. Paul region, with its high taxes and daunting winter climate, expanded primarily by developing a diversified homegrown industrial base, mainly in medical technology built from local expertise in health care.

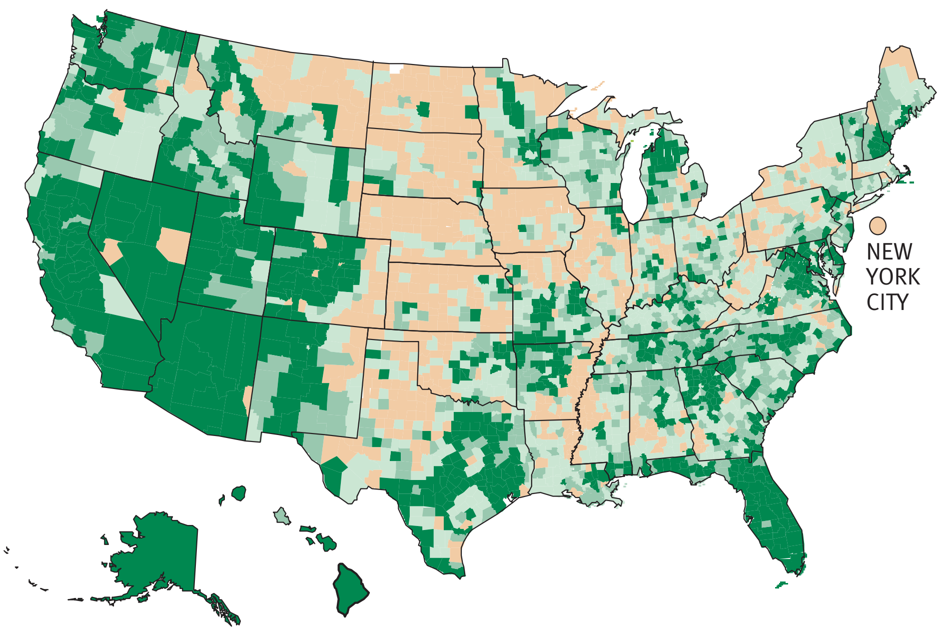
High-tech, of course, has driven the spectacular growth apparent in many areas, notably in Silicon Valley and Seattle, but an older technology was perhaps just as important for the South. The spread of air-conditioning after World War II made Southern living tolerable. This, together with the growth of the interstate highway system and long-distance trucking, low labor costs, and weak unions, allowed the South to compete aggressively with Northern manufacturers. Technology had the opposite effect in agricultural areas in the Great Plains. Although these places are generally prosperous, population has been declining since the 1930s because farms have been consolidating and becoming increasingly more productive, and so opportunities for young people there have declined.

If diversity and wealth beget a growing population, lack of diversity and poverty beget population decline, as happened in the Mississippi Delta, which has been losing people for most of the past 60 years. The delta, which runs from southern Missouri to Vicksburg, Miss., and northern Louisiana and includes counties in four states, has one of the poorest, least educated populations in the U.S., a major deterrent to modern industry. The delta is traditionally a land of sharecroppers, but since 1950 technology has reduced the need for unskilled field labor. So young people, particularly those with some education, went elsewhere.

High costs of doing business, including high taxes, may depress population size, as happened in New York City, which was a leading manufacturing center as recently as the 1960s. Low-cost areas such as the Atlanta region have benefited, although that city has also prospered because of its diversified economy, access to air and ground transportation, skilled workforce, and early abandonment of retrogressive racial attitudes.

Rising affluence has led a growing number of people to spend more on recreation and second homes. That has fueled population increases not only in places such as Florida and the Southwest but also in the Ozark Plateau of eastern Oklahoma-northern Arkansas-southern Missouri, the northern part of the lower Michigan peninsula and most of the nation's coastal areas.

—Rodger Doyle (rdoyle2@aol.com)



Change in population by county, 1970 – 1999 (percent)

Loss **0 – 24.9** **25 – 49.9** **50 or more**

SOURCE: U.S. Bureau of the Census

RODGER DOYLE

MEDICINE

DNA Junk and Lupus

When the trash collector doesn't come, the waste may become dangerous to health. A similar negligence might cause the severe autoimmune disease systemic lupus erythematosus, which affects more than one million people in the U.S. When a body cell dies, a crew of proteins quickly chops it up and clears the remnants. But if molecules such as DNA are left behind, antibodies can develop against them and lead to inflammation.

To test if failure to remove the DNA from dead cells can alone elicit lupus, researchers from the universities of Essen and Bochum in Germany, led by Tarik Möröy, created mice lacking the DNA-clearing enzyme called Dnase-1. In the June issue of *Nature Genetics* they report that after six to eight months, some of these genetically engineered mice had indeed developed antibodies against DNA and a form of kidney inflammation common in lupus. Because Dnase-1 activity is also low in lupus patients, treating them with the enzyme might improve their condition. *—Julia Karow*

PSYCHOLOGY

Size Doesn't Matter

Big families ≠ low IQ

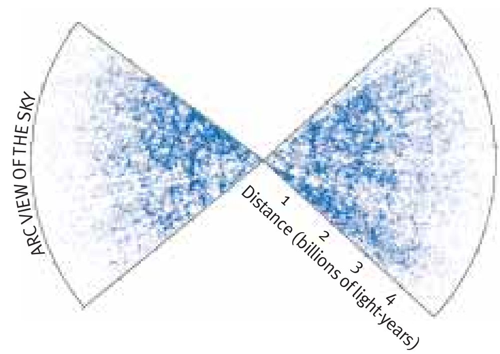
K. SHAMSI-BASHA *The Image Works*

Since the mid-1970s psychologists have maintained that children in large families tend to score lower on IQ tests. But data appearing in the June *American Psychologist* now show that birth order and family size have no bearing on a kid's IQ. Over a six-year period, investigators led by Joseph Lee Rodgers of the University of Oklahoma gave IQ tests to 5,107 children born to participants of the National Longitudinal Survey of Youth, a random sample of families started in 1972. IQ scores were then compared within families, not just between families—something earlier studies had not done. The researchers failed to find any correlation between family size, birth order and IQ. Instead they found that women with lower IQ scores tend to have larger families and discovered a link between the mother's IQ and those of her children, no matter how many there are. Parents should now feel comfortable about having more than 1.85 kids. *—Diane Martindale*

GALAXY MAPPING

Cosmic Cartography

Cosmologists have a reputation for thinking about ridiculously large things (the universe) or ridiculously small things (particles). But one of their greatest challenges has been to unravel what happens on medium scales—at cosmic distances where matter goes from being clumpy on small scales to being comparatively smooth on larger ones. Now an ongoing galaxy-mapping effort has seen the transition: it begins to occur at around 300 million light-years. The arrangement of matter on such scales reflects the overall density of the universe, and the results agree with the current consensus among cosmologists. The findings come from the Two-Degree Field (2dF) galaxy redshift survey. It ultimately intends to plot the positions of 250,000 galaxies in two slices of the sky, each about 75 degrees across, eight to 15 degrees thick, and four billion light-years deep—more than twice as deep as the previous record-holder. The survey team, led by Matthew Colless of the Australian National University and John A. Peacock of the University of Edinburgh, described its progress at the June American Astronomical Society meeting. *—George Musser*



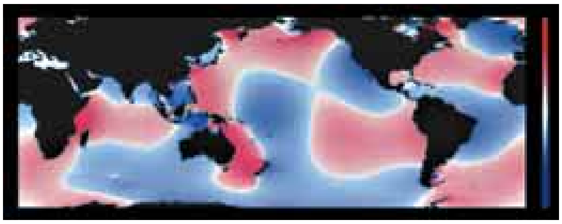
TWO-DEGREE FIELD GALAXY REDSHIFT SURVEY AND ANGLO-AUSTRALIAN OBSERVATORY

AS BIG AS IT GETS: Galaxies belong to clusters, which belong to superclusters, which belong to "walls," which belong to ... nothing. The walls in this map of 106,000 galaxies are not part of any larger subunit.

OCEANOGRAPHY

Sea Change for Tides

Computer models that mimic the circulation of the world's oceans, the primary engine of climate change, are programmed to ignore tides. That's because the moon's gravity tugs the oceans back and forth but doesn't mix them up and down, which is the way the ocean absorbs and releases heat. But now a report in the June 15 *Nature,* based on sea-level measurements by the TOPEX/Poseidon satellite, suggests that energy dispersed from lunar tides could drive some of the vertical mixing. Friction between the water and shallow coastlines diffuses most tidal energy but does not account for about 30 percent of it. That energy is being rerouted by underwater mountain chains and other rough spots, such as the Mid-Atlantic Ridge. Globally, these rough spots scatter about a trillion watts of energy—half the power needed to return deep waters to the surface. —*Sarah Simpson*



HIGH TIDE (*pink*)

LOW TIDE (*blue*)

NASA GODDARD SPACEFLIGHT CENTER AND JET PROPULSION LABORATORY; SCIENTIFIC VISUALIZATION STUDIO; TELEVISION PRODUCTION NASA-TV/GSFC

DATA POINTS

The Need for Zzz's

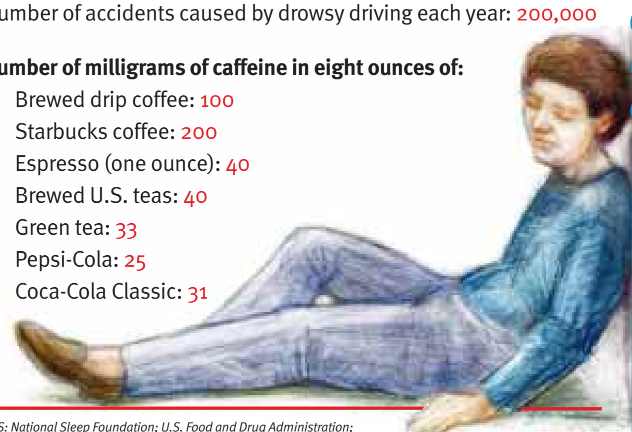
Average number of hours a day a U.S. adult sleeps today: 7
Number of hours in 1910: 9
Percentage of adults who sleep 6 ½ hours or less: 33

Percentage of employees who would nap at work if allowed: 33
Percentage of employers who allow napping: 16

Percentage of adults who admit to driving while sleepy: 51
Percentage of adults who admit to driving faster while sleepy: 12
Number of accidents caused by drowsy driving each year: 200,000

Number of milligrams of caffeine in eight ounces of:

- Brewed drip coffee: 100
- Starbucks coffee: 200
- Espresso (one ounce): 40
- Brewed U.S. teas: 40
- Green tea: 33
- Pepsi-Cola: 25
- Coca-Cola Classic: 31



SHARON STEUER

SOURCES: National Sleep Foundation; U.S. Food and Drug Administration; International Food Information Council; Starbucks; Mayo Clinic; Pepsico; Coca-Cola Company

BIOLOGY

Atomic-Force Geckos

How can a gecko climb up a glass wall and hang from one toe? In the June 8 *Nature* scientists offer a solution to this long-standing mystery. A gecko foot bears about half a million hairs, or setae, each of which splits into hundreds of ends, like a brush (*top photograph*). The maximum adhesive force of a single seta reaches about 200 micronewtons, nearly 10 times higher than previously estimated from studies of whole animals. This means that if all its setae operated at once and at full force, the gecko could carry 40 kilograms. The setae let go when tipped at 30 degrees, explaining the gecko's "toe-peeling" walking style. Van der Waals forces, the weak attractive forces between atoms and molecules, most likely explain the adhesion; they require a distance between foot and surface of no more than one atom (also see www.sciam.com/explorations/2000/061900Gecko). —*J.K.*

KELLAR AUTUMN *Lewis and Clark College*

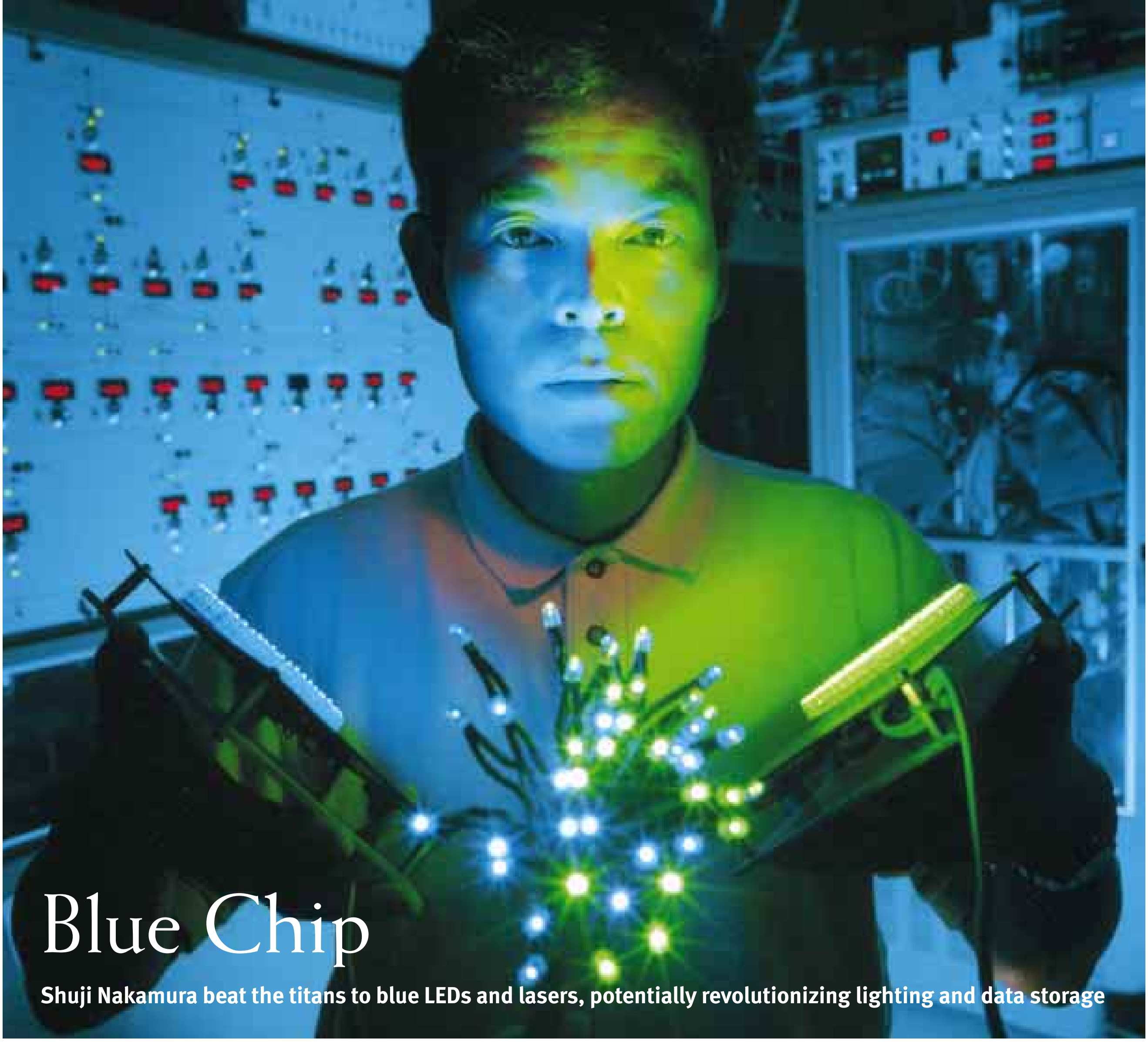
Sticky secret revealed

CHRIS MATTISON *Frank Lane Picture Agency/Corbis*

MEDIA CRITICISM

A Dose of Our Own Medicine

Mea culpa. A study in the June 1 *New England Journal of Medicine* shows that we journalists could probably do our jobs better. Stories about new medications often exaggerate benefits, ignore risks, overlook costs and fail to comment on financial ties to drug manufacturers. The study, co-authored by medical researchers and a journalist, analyzed 207 news stories and found that only 124 reported benefits quantitatively. And 103 of those gave the results in relative terms only—articles about the drug alendronate, for example, touted its ability to reduce hip fractures in people with osteoporosis by 50 percent without mentioning that the reduction took the risk down from an already low 2 percent to 1 percent. Only 98 stories mentioned possible harm from the drugs, and only 63 cited cost. An accompanying editorial reminds journalists to be skeptical. The same counsel applies to consumers of medical news. —*Steve Mirsky*



Blue Chip

Shuji Nakamura beat the titans to blue LEDs and lasers, potentially revolutionizing lighting and data storage

SANTA BARBARA, CALIF.—I press a button on the pocket light-emitting diode tester, and three specks of plastic and semiconductor shoot out blue and green rays intense enough to hurt my eyes. The two blue devices emit a furious cerulean with the slightest hint of violet. The green is sharp and rich—not that ghastly yellowish hue that had to do if you wanted a "green" LED until recently.

Until, that is, the man who is grinning at me, Shuji Nakamura, got some very bright ideas.

Nakamura, the newest addition to the engineering faculty at the University of California at Santa Barbara, stunned colleagues late in 1999, when he revealed that he was leaving Nichia Corporation, a once obscure Japanese maker of phosphors for cathode-ray tubes and fluorescent lights. Thanks to Nakamura, Nichia now fabricates the world's best blue and green LEDs and the only commercially available blue-violet semiconductor lasers. At a time when invention is dominated by faceless teams at huge corporations, he showed that an inventor with enough talent and determination can triumph despite daunting disadvantages.

For more than 25 years, LEDs were like a third of a rainbow. Red, orange, yellow and that yellowish green were all you could get. Engineers wanted blue and true green because with those colors, along with the red they already had, they could build fabulous things, such as a white-light-emitting device as much as 12 times more efficient and longer-lasting than an ordinary lightbulb. Small wonder, then, that analysts say LEDs are poised to revolutionize the lighting industry and move beyond their familiar role as mere indicator lights. In the meantime, colored LEDs are being deployed as traffic lights and in displays, the biggest being the eight-story-tall Nasdaq display in New York City's Times Square. And a blue semiconductor laser, similar to an LED, will soon quadruple the storage capacity of DVD and CD players and the resolution of laser printers.

Most of the milestones on the way to these optoelectronics triumphs took place, oddly enough, on the island of Shikoku, something of a backwater in the Japanese chain. There Nakamura was born, raised and educated at the University of Tokushima. He earned a master's degree in 1979 and then took a job at Nichia, basically because it was nearby, on Shikoku.

Right after he joined the company, the young Nakamura was put to work on gallium phosphide crystals, which were used to make red and yellowish green LEDs. The research budget was tight, so Nakamura had to build all the necessary equipment on his own. That meant he had to teach himself such tricky and esoteric chores as welding quartz.

In 1982 he began producing gallium phosphide crystals that were as good as

ERIC O'CONNELL (*photograph*); BRIAN CARRELEJO (*electronic circuit for LEDs*); NICHIA AMERICA CORPORATION (*LEDs*) anything Nichia's larger rivals—including Sanyo, Sharp, Stanley Electric, Rohm and Toshiba—were putting out. Unfortunately, most customers bought from the larger, well-known companies, leaving Nichia only a sliver of the LED pie. Over the next six years, Nakamura went through essentially the same frustrations with gallium arsenide crystals and then with complete red and infrared LEDs.

Strangely, Nichia's sales department blamed Nakamura for the disappointing figures, and some senior co-workers wanted him to resign. "I became very angry," Nakamura recalls. But rather than let them drive him away, he resolved to aim higher. He knew that optoelectronics' holy grail was a blue-light emitter, and he decided to get into the fray.

Nakamura's boss, the R&D manager, thought he was "crazy," as he tells it, and wouldn't support him. So in January 1988 Nakamura bypassed his boss and marched into the office of Nichia's CEO, Nobuo Ogawa, to demand $3.3 million in research funding and a year off to go to the University of Florida to study a semiconductor-fabrication technology called metallorganic chemical vapor deposition (MOCVD) that channeled hot gases to create thin films on substrates. MOCVD was then emerging as the technology of choice for producing certain exotic semiconductors. It was an outrageous move in the feudal, seniority-based Japanese corporate system. Much to Nakamura's amazement, however, Ogawa simply agreed to all his terms.

At the Florida lab, he found that only parts that could be assembled into an MOCVD system were available. And it turned out that Nakamura was just the guy to do it: lacking a doctorate and a list of published papers, Nakamura says he was "treated like an engineer, not a researcher." Building the MOCVD machine took him 10 months, working seven days a week, 16 hours a day.

Returning to Nichia in March 1989 to begin work on blue-light devices, he had to choose between the two main semiconductor types. No contest: Nakamura picked gallium nitride, because all the giants of industry and academia were pursuing zinc selenide, and he was sick of playing the same game as the titans. They avoided gallium nitride because a necessary form of the material (called *p*-type) could not be made in commercially useful amounts.

Over the next 10 years, as he coaxed more and more light out of gallium nitride and eclipsed his competitors, Nakamura put together a string of achievements that for genius and sheer improbability is as impressive as any other accomplishment in the history of semiconductor research. And it is all documented in a trail of literature almost as stunning. Between 1991 and 1999 he authored or co-authored 146 technical papers, six books and 10 book chapters on gallium nitride semiconductors. The output is all the more amazing because it was accomplished in secret: CEO Ogawa, fearing disclosure of secrets, forbade Nichia employees from publishing or speaking at conferences. By 1994 Nakamura's body of work was so prodigious that the University of Tokushima awarded him a doctorate in engineering.

SHUJI NAKAMURA: FAST FACTS

- **Born in Seto-cho, Nishiuwa-gun, Ehime Prefecture, on Shikoku island, in 1954**
- **Wife, Hiroko Nakamura, and three daughters, Hitomi, Fumie and Arisa**
- **As a boy, he was inspired by the comic book *Tetsuwan Atom*, about a robot, written by the great Japanese comic artist Osamu Tezuka**
- **Favorite foods: Larmen and udon noodles; uni (sea urchin) sushi**

The foundation of Nakamura's success was a deep understanding not only of semiconductor crystal growth but, more important, of the machines that accomplished it. The active layer in his experimental LED, where electrons and electron deficiencies called holes combined and released photons, was a thin film of indium gallium nitride grown on gallium nitride. Commercially available MOCVD machines could not grow an indium gallium nitride film good enough to emit light brightly, so Nakamura began modifying his setup. From his years of building reactors, furnaces and MOCVD machines, he knew how to weld quartz—which enabled him to alter quickly the conduits that conveyed the superhot reactants in an MOCVD machine.

Every morning Nakamura modified the reactor. Every afternoon he grew four or five samples. After about two years, he hit on the configuration that would put him way ahead of the pack. In a conventional MOCVD system, semiconductors are created as reactant gases flow over a substrate, parallel to its surface. In Nakamura's system, one gas flows parallel to and the other flows perpendicularly to the surface. The configuration, which he calls "two-flow MOCVD," suppresses thermal convection currents and cools the reactant gases, leading to more stable reactions and better films.

The other major obstacle to a mass-producible LED fell in 1992, when he invented a heat-based process to produce commercial quantities of *p*-type gallium nitride. But to get a dependable laser, he still had to find a way to minimize the enormous density of defects in gallium nitride crystals. Taking inspiration from a talk by NEC researchers in 1997, Nakamura grew a layer of silicon dioxide strategically within the gallium nitride crystal to block some of the defects. By the end of the year he had increased the lifetime of his blue semiconductor lasers from about 300 hours to the 10,000 hours needed for a commercial product.

Early in 1999 Nichia began selling five-milliwatt blue semiconductor lasers and, later, violet ones with a wavelength of 405 nanometers, the shortest ever for a semiconductor laser. Nakamura also produced blue lasers with power levels above 30 milliwatts; he declines to give a precise figure (the levels necessary for laser printers are around 50 to 60 milliwatts).

Last October, having done everything he wanted to with gallium nitride and weary of a Japanese industrial R&D system that he characterizes as "communist," Nakamura decided to leave Nichia. Although his inventions had swelled Nichia's annual profits from under $100 million to over $400 million, Nakamura was being paid only $100,000 a year, he says. Among the 17 job offers he got in the space of four weeks was one from a U.S. company that offered him $500,000 a year and stock options worth $10 million. "It was unbelievable to me," he relates.

He was ready to sign with the company, but a professor at one of the universities that was courting him advised him that if he took an industrial job, Nichia—which held the patents on all his gallium nitride breakthroughs—would sue him if he did anything even remotely related. After mulling things over, Nakamura accepted an offer from the University of California at Santa Barbara.

Having earned a nice spot in the semiconductor pantheon, the 46-year-old Nakamura is as restless and driven as ever. Asked what he wants to do now, he replies, "Here I can start a venture company—in five or 10 years, if I could invent a new device." He says, laughing: "I want to achieve the American dream." —*Glenn Zorpette*

For an enhanced and more detailed version of this story, go to www.sciam.com

ENGINEERING_SUPERCONDUCTIVITY

No Resistance

High-temperature superconductors start finding real-world uses

For a few months in 1987, it seemed the world was about to change. Trains would fly on magnetic cushions, computers would be faster, electric power cheaper, new medical scanners would sprout in doctors' offices and more. The reason for this overheated optimism was the discovery by **IBM** scientists in Zurich, namely, J. Georg Bednorz and K. Alex Müller, of a new kind of superconductor, an almost miraculous material that conducts electricity without any loss of energy. Superconductors had been around since 1911, but all known superconductors worked at near absolute zero, which made them impractical for all but the most specialized applications.

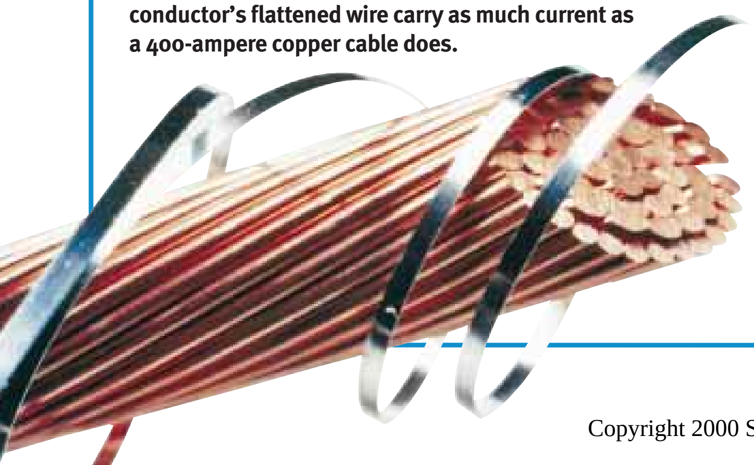
The discovery led to a class of oxide superconductor working well above the temperature of liquid nitrogen. Boiling at 77 kelvins, liquid nitrogen is much less expensive to make and far easier to handle than liquid helium, which cools conventional superconductors. (Physicists still hope to find a material that superconducts at room temperature—possibly the next best thing to perpetual motion.) Gradually, researchers have found ways to craft high-temperature superconductors into useful magnetic components for research and for medical diagnostics and have even manufactured motors, current limiters and other devices for demonstration purposes. But now, more than a decade after their discovery, they are entering two markets closer to the consumer realm—power lines and wireless communications.

The largest obstacle to making commercial high-temperature superconducting cables is that the materials are ceramics and therefore as fragile as a Ming vase. In 1987 Greg Yurek, a metallurgist from the **Massachusetts Institute of Technology**, realized that just as brittle glass can be drawn into filaments to make flexible fiber optics, the same thing could be done with high-temperature superconductors. "That insight led to the fundamental patent in this field," says John Howe of **American Superconductor** in Westborough, Mass., the company that Yurek would go on to found.

Yurek's basic concept is to place small granules of the superconducting material in a silver tube, or billet, about the diameter of a quarter. These billets are drawn into thin filaments, which are bundled and placed in another silver tube. That tube is flattened to make a superconducting ribbon that is reasonably flexible, although nowhere near as bendable as copper wire.

Two years ago, according to Howe, the price of superconducting wire was 50 times that of comparable copper cable. American Superconductor is now building a new plant to make the wire, and "by achieving scale economies, we'll bring the cost down to about two times the cost of copper," Howe predicts. The firm maintains a partnership with **Pirelli Cables and Systems**, based in Milan, Italy, to develop superconducting transmission lines.

HIGH CAPACITY: **Three strands of American Superconductor's flattened wire carry as much current as a 400-ampere copper cable does.**



AMERICAN SUPERCONDUCTOR

Engineers at **Southwire**, a cable manufacturer in Carrollton, Ga., are among the first to make practical cables out of superconducting wire. This past February, Southwire began to supply power to three of its manufacturing plants by superconducting cables. It designed the 100-foot-long cables in a collaboration with the **Oak Ridge** and **Argonne National Laboratories**, the **U.S. Department of Energy** and several industrial partners, including **Intermagnetics General** in Latham, N.Y., which supplied the superconducting wire. The cable consists of hollow pipe through which liquid-nitrogen coolant flows. Surrounding this pipe are layers of superconducting wires and insulation, all of which are encased in a double-walled thermos bottle. The entire assembly is five inches in diameter but will be thinner in production models. "It being our first, we were being very conservative," says project manager R. L. Hughey.

Still, it is thinner than a copper wire carrying the same current, which is the point. All else being equal, the savings achieved with the more efficient superconducting cable ordinarily isn't high enough to make it worth the expense. Rather "the main gain is that because superconducting wire has virtually no resistance, you can push huge amounts of power through it," Hughey explains, thereby solving the most intractable problem facing power engineers in cities: where to put wires in otherwise jam-packed cable channels. The benefits are clear from the system American Superconductor is building for **Detroit Edison**'s Frisbee substation: 18,000 pounds of 1930s-vintage copper cable running through nine ducts will be replaced with 250 pounds of superconductor in three ducts, leaving six free for future expansion. Other notable power applications are superconducting magnetic-energy storage systems, which can stabilize disturbances on power grids, and, further away, lightweight motors and transformers.

Superconducting devices are also beginning to make headway into wireless communications as filters. An ideal filter selects only a single frequency, but in practice, electrical resistance causes filters to tune in a small range of frequencies. Superconducting filters, because they lack electrical resistance, are far more discriminating. In addition, less of the signal is lost between the antenna and the receiver, making them especially sensitive. These two factors are important in cellular communications, which must operate in an extremely crowded radio spectrum and pick up signals from low-powered transmitters.

"This was a very ambitious enterprise when we started in 1987," says Robert B. Hammond, senior vice president and chief technical officer of **Superconductor Technologies**, based in Santa Barbara, Calif. To make superconducting filters, the firm had to solve many problems. It developed methods of making circuits by depositing thin films of superconductors and designed a vacuum pack to insulate the circuits. Connecting the circuit to the real world proved challenging, because the connections had to be good electrical conductors and poor thermal conductors—two properties that do not normally go together.

Finally, it had to invent a cooling system that could keep the


IGC-SuperPower

WIRED: Southwire powers some industrial plants via three 100-foot-long superconducting cables.

circuit chilled for years at a time, because these filters would be used on remote radio towers. Hammond says it developed a tiny refrigerator, "a little smaller than a half-gallon milk carton," in which a mini engine compresses and expands helium gas. "Our belief is that these things will be used broadly to extend the range of base stations and decrease the handset power by a factor of two or more," Hammond explains. Other companies working on similar products include **Illinois Superconductor** in Mt. Prospect, Ill., whose filter boosted wireless phone capacity by 70 percent in a demonstration last year, and **Conductus** in Sunnyvale, Calif.

No firm is profiting from high-temperature superconductors yet, and price remains a roadblock to wider acceptance. But with ongoing progress in a market that could be worth $30 billion by 2020, high-temperature superconductors just might justify some of the hype of 1987.

—Bruce Schechter

BRUCE SCHECHTER is a freelance writer based in Brooklyn, N.Y.

Different Stripes

Physicists still struggle to explain high-temperature superconductivity

Despite researchers' best efforts, high-temperature superconductivity remains a mystery. In the past few years, many physicists have studied the idea that organized lines of electric charge, known as stripes, could produce the resistanceless flow of current and other bizarre properties. In April two groups announced direct experimental evidence for this model in the superconductor known as YBCO (yttrium barium copper oxide). As has so often occurred in this field, the significance of the results is hotly debated, and barely a month later a third group reported studies inconsistent with stripes.

High-temperature superconductors are multilayered, ceramic crystals. All the superconducting action takes place in planes of copper and oxygen atoms sandwiched between layers of other elements, such as yttrium and barium. The density of electric charges free to move about on the copper oxide "meat" of the sandwich depends on the precise recipe used for the "bread." In the case of YBCO, excess oxygen in the yttrium barium oxide bread soaks up electrons from the copper oxide meat, leaving behind holes, which can be thought of as positively charged particles.

Superconductivity arises when the holes form loosely bound pairs that undergo Bose-Einstein condensation—they all collect in one quantum state. Such condensate fluids flow en masse without friction. Conventional superconductors involve condensates of electron pairs held together by a well-understood interaction, but no one knows what pairs up the holes in cuprate superconductors.

When no holes are present, the cuprate layers are like chessboards, each square representing a copper atom with its intrinsic magnetic field pointing one way ("black square") or the other ("white square"). Individual holes introduced to this rigid arrangement cannot move about easily, because the motion would disrupt the chessboard arrangement. If enough holes are in the plane, they may spontaneously collect together along rows, forming "stripes" of charge. Holes can move readily along such stripes without upsetting the chessboard pattern elsewhere. Stripes fixed in place cannot produce superconducting pairs of holes, but dynamic stripes, which meander across the chessboard, can.

Such meandering stripes should also slightly displace atoms in the cuprate planes. Thirumalai Venkatesan of the University of Maryland and his co-workers fired helium ions through the channels formed by the rows of atoms in crystal planes and saw evidence of these displacements. As the crystal was cooled, the effect varied as expected if stripes form above superconducting temperatures and generate the required pairing of holes at lower temperatures. Herbert A. Mook of Oak Ridge National Laboratory and his colleagues found direct evidence for meandering stripes as well. The researchers fired neutrons into YBCO and observed that they diffracted in a manner characteristic of fluctuating one-dimensional structures in the material.

A proponent of stripes, Jan Zaanen of Leiden University in the Netherlands, says that these results "convincingly disprove more conventional explanations" of YBCO's behavior, which are founded on the idea of weakly interacting collective excitations, or quasi-particles, that behave much like individual electrons or holes. Such quasi-particles are the essence of Fermi liquid theory, which forms the foundation of physicists' understanding of metals, semiconductors and conventional superconductors. Physicists have long known that Fermi liquid theory must be modified for the cuprates. According to Zaanen, however, mere modifications cannot explain the effects seen by Venkatesan and Mook.

But there is a caveat: the clearest evidence of stripes in YBCO is in crystals that have less than the optimal number of holes for the most robust superconductivity. When Philippe Bourges of Léon Brillouin Laboratory in Saclay, France, and his group scattered neutrons from crystals of *optimally* doped YBCO, they obtained results consistent with conventional quasi-particle descriptions and inconsistent with simple stripes. Bourges believes the data from underdoped YBCO still have loopholes for alternative explanations. Stripes are "not of great importance for the superconducting mechanism," he says. For now the debate rages on, and Venkatesan suggests that the important process is the formation of distinct magnetic (chessboard) and charged regions, which may have shapes other than stripes in optimally doped superconductors.

—Graham P. Collins

Circles of Trust

How vouching for users beats encryption alone in maintaining privacy

LONDON—In a world of disembodied strangers, the issue of trust is complicated. Some governments seem to think there's a simple solution—just make everyone trackable. The British government, for example, talks quite a lot about nonrepudiable digital signatures without ever acknowledging that a piece of electronic information is never going to be perfectly bound to a human.

The notion that the security systems we've been relying on don't work for the mass market the way we'd hoped they would occurred to me last December. An e-commerce site sent me a message saying the certificates built into earlier versions of Netscape were expiring. If I wanted to keep using their site, I had to . . . upgrade my browser. First question: Why can't I just get updated copies of the certificates? Second question: What are certificates?

That part I knew. Certificates in their current incarnation are electronic strings of seeming gibberish that securely identify a person, organization or e-commerce site to my computer. Glancing at the settings of my Netscape browser, I see that the list of third-party authenticators includes American Express, Deutsche Bank and VeriSign, the last being the leading on-line certification authority. If I click on the button labeled "verify," the software performs some hidden black magic and pronounces the certificate verified. But how many consumers are going to understand why that works or how they can know that the verification is valid? The Web pages dedicated to explaining this mini crisis aren't much help, either, as they note that the only penalty for having an expired certificate is that you have to click on an extra dialogue box to establish a secure session. Well, so what? What exactly is VeriSign guaranteeing me?

This kind of question is the province of security experts such as Carl Ellison. I first heard Ellison address this issue at a 1997 London meeting that discussed government plans to set up a network of trusted third parties to help e-commerce flourish. These parties would be cryptographic-service providers that, like VeriSign, would authenticate transactions. The government's idea was that they would obviously be banks—organizations that the government knew how to regulate. Quite apart from the fact that most Britons hate their banks, in the real world neither our assurance of someone's identity nor our trust in them rests on authentication from a large third-party institution. Binding a key to a name is meaningless in terms of trust, because few names are unique.

Instead I determine that the letter from "John Gizzarelli" is authentic because it contains personal data and context, such as mentions of his wife, my sister Ellen. If the style seems doubtful, I might check the postmark, phone them or compare handwriting. I don't phone the bank and ask it to authenticate the letter.

DAVID SUTER

Unlike top-down proposals such as the British government's, the technical community has generally favored a more distributed plan. Look, for example, at the way PGP (Pretty Good Privacy), the well-known cryptographic software, handles authentication. It builds a web of trust by allowing users to authenticate one another's keys through digital signatures. Under this regime, if John wanted to verifiably bind himself to his key, he might refer users to my signature on his key. If they already trust me, they accept my verification; if not, they go to another link along the chain looking for someone to authenticate me. Either way, they are passed from peer to peer, much like in the England of Agatha Christie novels, where a new arrival in a rural village would bring a letter of introduction.

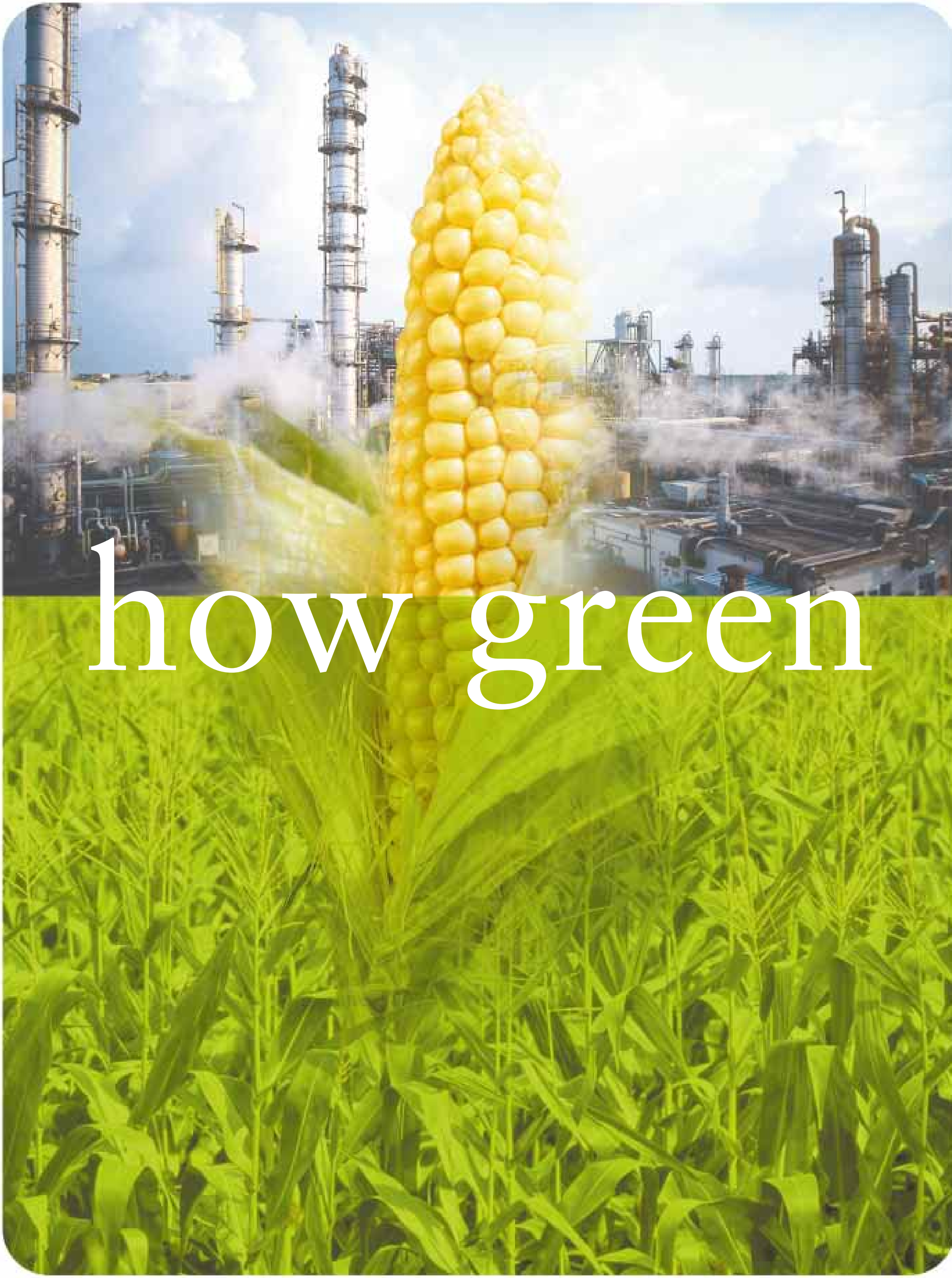
In his talk and in papers posted on the Web, Ellison's proposals are different. He advocates circles of trust, which are designed to grow together: local names, given meaning by their context and perhaps used only for a small number of purposes, rather than becoming a global identifier.

We may need to establish such circles of trust sooner than we think. One of the best moments at this year's Computers, Freedom and Privacy conference, held in April, came during science-fiction writer Neal Stephenson's presentation. He focused on threat, rather than trust, models. We still think, he argued, in terms of the 1950s obsession with a monolithic government that wants to know everything—Big Brother, in other words. And at that point he put up a slide with a cartoon drawing of an ordinary guy with an ordinary house and an unordinary picket fence: just one very large picket thrusting up into the sky, where a bird regarded it quizzically. That, he told us, was PGP.

Stephenson's point was not that PGP is ineffective—the program has stood up to nearly a decade of industrial-strength testing—but that the kind of intrusion it protects against is based on a model in which there is only one kind of threat. PGP can keep "them" from reading your data, but it can't stop people from analyzing your e-mail traffic and drawing conclusions from the frequency and volume of e-mail you exchange with particular people. Nor can it stop organizations from compiling profiles based on your interactions with them and exchanging that data to create a complete dossier. And it certainly can't stop the Love Bug and Resume viruses; you can use all available encryption to authenticate the source of the virus-laden messages, and the viruses will still enter your machine, because they genuinely do come from your friends and co-workers (or at least their machines).

Stephenson's proposed antidote to multiple threats was small pools of trust: people you know and trust who would vouch for those you don't know. These pools could grow and overlap to become a field of trust that would provide far more protection than that single picket could afford. Diffusion and multiple identities, it would seem, are our friends against diffuse and multiple threats. *—Wendy Grossman*

WENDY GROSSMAN, a frequent contributor to this column, is based in London.


how green

It is now technologically possible to make plastics using green plants rather than nonrenewable fossil fuels. But are these new plastics the environmental saviors researchers have hoped for?

by Tillman U. Gerngross and Steven C. Slater

are green plastics?

Driving down a dusty gravel road in central Iowa, a farmer gazes toward the horizon at rows of tall, leafy corn plants shuddering in the breeze as far as the eye can see. The farmer smiles to himself, because he knows something about his crop that few people realize. Not only are kernels of corn growing in the ears, but granules of plastic are sprouting in the stalks and leaves.

This idyllic notion of growing plastic, achievable in the foreseeable future, seems vastly more appealing than manufacturing plastic in petrochemical factories, which consume about 270 million tons of oil and gas every year worldwide. Fossil fuels provide both the power and the raw materials that transform crude oil into common plastics such as polystyrene, polyethylene and polypropylene. From milk jugs and soda bottles to clothing and car parts, it is difficult to imagine everyday life without plastics, but the sustainability of their production has increasingly been called into question. Known global reserves of oil are expected to run dry in approximately 80 years, natural gas in 70 years and coal in 700 years, but the economic impact of their depletion could hit much sooner. As the resources diminish, prices will go up—a reality that has not escaped the attention of policymakers. President Bill Clinton issued an executive order in August 1999 insisting that researchers work toward replacing fossil resources with plant material both as fuel and as raw material.

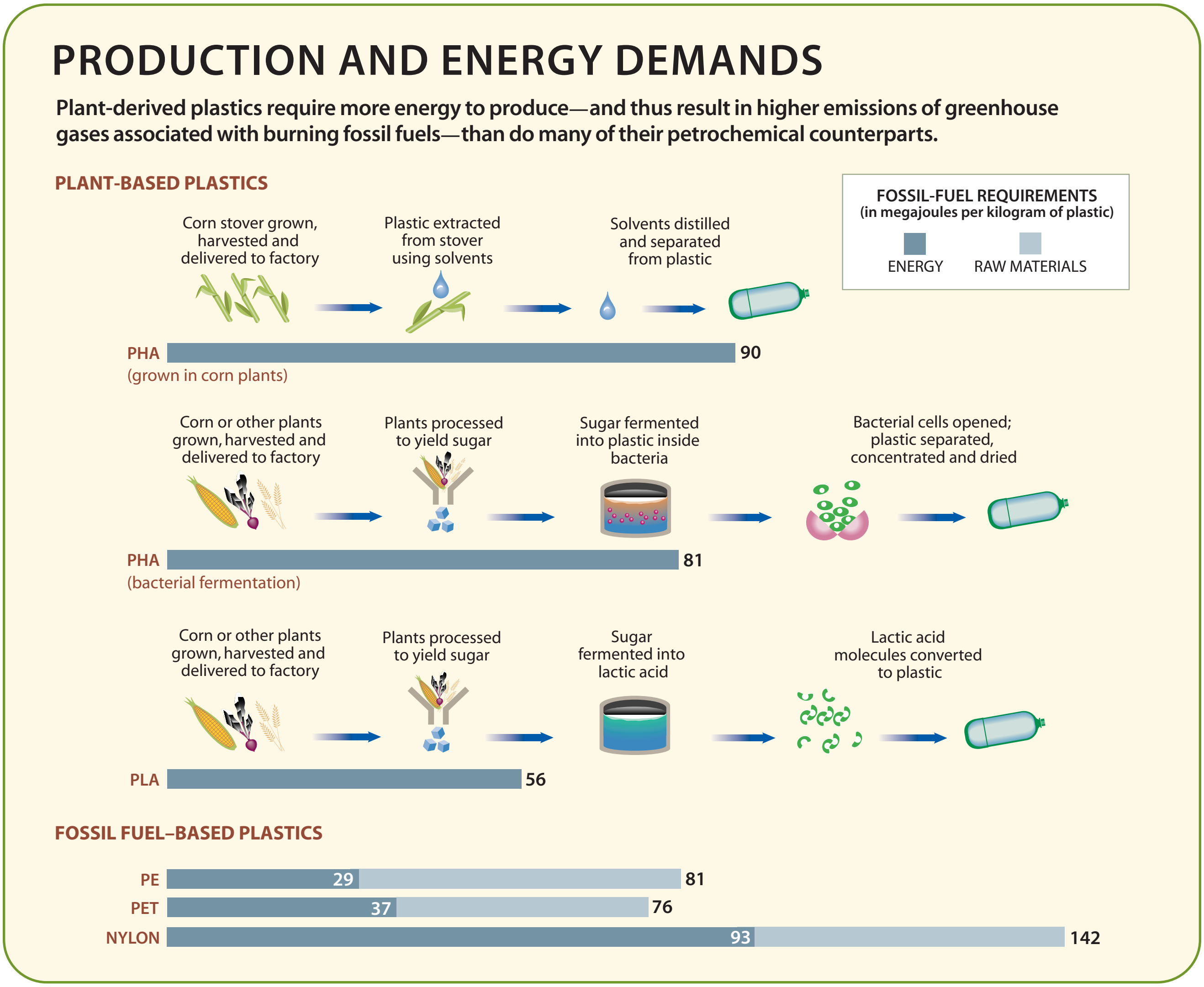
With those concerns in mind, biochemical engineers, including the two of us, were delighted by the discovery of how to grow plastic in plants. On the surface, this technological breakthrough seemed to be the final answer to the sustainability question, because this plant-based plastic would be "green" in two ways: it would be made from a renewable resource, and it would eventually break down, or biodegrade, upon disposal. Other types of plastics, also made from plants, hold similar appeal. Recent research, however, has raised doubts about the utility of these approaches. For one, biodegradability has a hidden cost: the biological breakdown of plastics releases carbon dioxide and methane, heat-trapping greenhouse gases that international efforts currently aim to reduce. What is more, fossil fuels would still be needed to power the process that extracts the plastic from the plants, an energy requirement that we discovered is much greater than anyone had thought. Successfully making green plastics depends on whether researchers can overcome these energy-consumption obstacles economically—and without creating additional environmental burdens.

Traditional manufacturing of plastics uses a surprisingly large amount of fossil fuel. Automobiles, trucks, jets and power plants account for more than 90 percent of the output from crude-oil refineries, but plastics consume the bulk of the remainder, around 80 million tons a year in the U.S. alone. To date, the efforts of the biotechnology and agricultural industries to replace conventional plastics with plant-derived alternatives have embraced three main approaches: converting plant sugars into plastic, producing plastic inside microorganisms, and growing plastic in corn and other crops.

Cargill, an agricultural business giant, and Dow Chemical, a top chemical firm, joined forces three years ago to develop the

GROWING PLASTICS in plants once seemed to be an innovative way to lessen the global demand for fossil fuels.

TOM DRAPER DESIGN



first approach, which turns sugar from corn and other plants into a plastic called polylactide (PLA). Microorganisms transform the sugar into lactic acid, and another step chemically links the molecules of lactic acid into chains of plastic with attributes similar to polyethylene terephthalate (PET), a petrochemical plastic used in soda bottles and clothing fibers.

Looking for new products based on corn sugar was a natural extension of Cargill's activities within the existing corn-wet-milling industry, which converts corn grain to products such as high-fructose corn syrup, citric acid, vegetable oil, bioethanol and animal feed. In 1999 this industry processed almost 39 million tons of corn—roughly 15 percent of the entire U.S. harvest for that year. Indeed, Cargill Dow earlier this year launched a $300-million effort to begin mass-producing its new plastic, NatureWorks™ PLA, by the end of 2001 [*see box on page 40*].

Other companies, including Imperial Chemical Industries, developed ways to produce a second plastic, called polyhydroxyalkanoate (PHA). Like PLA, PHA is made from plant sugar and is biodegradable. In the case of PHA, however, the bacterium *Ralstonia eutropha* converts sugar directly into plastic. PLA requires a chemical step outside the organism to synthesize the plastic, but PHA naturally accumulates within the microbes as granules that can constitute up to 90 percent of a single cell's mass.

In response to the oil crises of the 1970s, Imperial Chemical Industries established an industrial-scale fermentation process in which microorganisms busily converted plant sugar into several tons of PHA a year. Other companies molded the plastic into commercial items such as biodegradable razors and shampoo bottles and sold them in niche markets, but this plastic turned out to cost substantially more than its fossil fuel–based counterparts and offered no performance advantages other than biodegradability. Monsanto bought the process and associated patents in 1995, but profitability remained elusive.

Many corporate and academic groups, including Monsanto, have since channeled their efforts to produce PHA into the third approach: growing the plastic in plants. Modifying the genetic makeup of an agricultural crop so that it could synthesize plastic as it grew would eliminate the fermentation process altogether. Instead of growing the crop, harvesting it, processing the plants to yield sugar and fermenting the sugar to convert it to plastic, one could produce the plastic directly in the plant. Many researchers viewed this approach as the most efficient—and most elegant—solution for making plastic from a renewable resource. Numerous groups were (and still are) in hot pursuit of this goal.

In the mid-1980s one of us (Slater) was part of a group that isolated the genes that enable the bacteria to make plastic. Investigators predicted that inserting these enzymes into a plant would drive the conversion of acetyl coenzyme A—a compound that forms naturally as the plant converts sunlight into energy—into a type of plastic. In 1992 a collaboration of scientists at Michigan State University and James Madison University first accomplished this task. The researchers genetically engineered the plant *Arabidopsis thaliana* to produce a brittle type of PHA. Two years later Monsanto began working to produce a more flexible PHA within a common agricultural plant: corn.

So that plastic production would not compete with food production, the researchers targeted part of the corn plant that is not typically harvested—the leaves and stem, together called the stover. Growing plastic in stover would still allow farmers to harvest the corn grain with a traditional combine; they could comb the fields a second time to remove the plastic-containing stalks and leaves. Unlike production of PLA and PHA made by fermentation, which theoretically compete for land used to grow crops for other purposes, growing PHA in corn stover would enable both grain and plastic to be reaped from the same field. (Using plants that can grow in marginal environments, such as switchgrass, would also avoid competition between plastic production and other needs for land.)

The Problem: Energy and Emissions

Researchers have made significant technological progress toward increasing the amount of plastic in the plant and altering the composition of the plastic to give it useful properties. Although these results are encouraging when viewed individually, achieving both a useful composition *and* high plastic content in the plant turns out to be difficult. The chloroplasts of the leaves have so far shown themselves to be the best location for producing plastic. But the chloroplast is the green organelle that captures light, and high concentrations of plastic could thus inhibit photosynthesis and reduce grain yields.

The challenges of separating the plastic from the plant, too, are formidable. Researchers at Monsanto originally viewed the extraction facility as an adjunct to an existing corn-processing plant. But when they designed a theoretical facility, they determined that extracting and collecting the plastic would require large amounts of solvent, which would have to be recovered after use. This processing infrastructure rivaled existing petrochemical plastic factories in magnitude and exceeded the size of the original corn mill.

Given sufficient time and funding, researchers could overcome these technical obstacles. Both of us, in fact, had planned for the development of biodegradable plastics to fill the next several years of our research agendas. But a greater concern has made us question whether those solutions are worth pursuing. When we calculated all the energy and raw materials required for each step of growing PHA in plants—harvesting and drying the corn stover, extracting PHA from the stover, purifying the plastic, separating and recycling the solvent, and blending the plastic to produce a resin—we discovered that this approach would consume even more fossil resources than most petrochemical manufacturing routes.

In our most recent study, completed this past spring, we and our colleagues found that making one kilogram of PHA from genetically modified corn plants would require about 300 percent more energy than the 29 megajoules needed to manufacture an equal amount of fossil fuel–based polyethylene (PE). To our disappointment, the benefit of using corn instead of oil as a raw material could not offset this substantially higher energy demand.

Based on current patterns of energy use in the corn-processing industry, it would take 2.65 kilograms of fossil fuel to power the production of a single kilogram of PHA. Using data collected by the Association of European Plastics Manufacturers for 36 European plastic factories, we estimated that one kilogram of polyethylene, in contrast, requires about 2.2 kilograms of oil and natural gas, nearly half of which ends up in the final product. That means only 60 percent of the total—or 1.3 kilograms—is burned to generate energy.

Given this comparison, it is impossible to argue that plastic grown in corn and extracted with energy from fossil fuels would conserve fossil resources. What is gained by substituting the renewable resource for the finite one is lost in the additional requirement for energy. In an earlier study, one of us (Gerngross) discovered that producing a kilogram of PHA by microbial fermentation requires a similar quantity—2.39 kilograms—of fossil fuel. These disheartening realizations are part of the reason that Monsanto, the technological leader in the area of plant-derived PHA, announced late last year that it would terminate development of these plastic-production systems.

Growing PHA in corn stover would enable both grain and plastic to be reaped from the same field.

The only plant-based plastic that is currently being commercialized is Cargill Dow's PLA. Fueling this process requires 20 to 50 percent fewer fossil resources than does making plastics from oil, but it is still significantly more energy intensive than most petrochemical processes are. Company officials anticipate eventually reducing the energy requirement. The process has yet to profit from the decades of work that have benefited the petrochemical industry. Developing alternative plant-sugar sources that require less energy to process, such as wheat and beets, is one way to attenuate the use of fossil fuels. In the meantime, scientists at Cargill Dow estimate that the first PLA manufacturing facility, now being built in Blair, Neb., will expend at most 56 megajoules of energy for every kilogram of plastic—50 percent more than is needed for PET but 40 percent less than for nylon, another of PLA's petrochemical competitors.

The energy necessary for producing plant-derived plastics gives rise to a second, perhaps even greater, environmental concern. Fossil oil is the primary resource for conventional plastic production, but making plastic from plants depends mainly on coal and natural gas, which are used to power the corn-farming and corn-processing industries. Any of the plant-based methods, therefore, involve switching from a less abundant fuel (oil) to a more abundant one (coal). Some experts argue that this switch is a step toward sustainability. Missing in this logic, however, is the fact that all

GREEN PLASTIC GETS PRACTICAL

Patrick Gruber, vice president of technology for Cargill Dow, answers questions about his company's new plant-derived plastic.

How will NatureWorks™ PLA compete with petrochemical plastics?

NatureWorks™ PLA combines several attributes into a single family of plastics. Its glossiness and ability to retain twists and folds better than its petrochemical counterparts, for example, appeal to companies that are developing PLA for candy wrappers and other kinds of consumer packaging. PLA also offers fabric manufacturers a natural fiber that can compete with synthetics, such as nylon, in both performance and ease of processing. Overall, industry sources have identified several billion pounds of market potential for PLA in areas such as apparel, activewear, hygiene products, carpet fibers and packaging.

What are the environmental advantages of PLA?

Because we use plant sugar rather than fossil fuels as the raw material for PLA, its production consumes 20 to 50 percent fewer fossil resources than do conventional plastics. PLA can be broken down into its original chemical components for reuse, or it can be recycled. One of our customers already plans to use PLA in recyclable carpet tiles. PLA will also biodegrade, much in the way that paper does, in municipal composting facilities. For these reasons, PLA will reduce society's dependency on fossil fuels while providing products that fit current disposal methods. These clear environmental benefits of PLA are a bonus—we believe that people will buy this plastic primarily because it performs well and can compete with existing technologies.

Do these benefits offset the fact that the energy required to produce PLA is greater than that needed to produce some petrochemical plastics?

It is important to realize that our PLA-manufacturing technology is only 10 years old and has yet to profit from the nearly 100 years during which petrochemical-plastic manufacturing has been improving. Even our first manufacturing facility, now being built in Nebraska, will use only 40 percent of the fossil-fuel energy that is required to power the production of conventional nylon. As our scientists and engineers optimize the production of PLA, we expect to reduce the energy requirements of our second and third manufacturing facilities, targeted for construction as early as 2004, by as much as 50 percent.

Do you plan to address what Gerngross and Slater call "the environmental shortcomings" of PLA?

Yes. Not only are we developing production methods that require less energy, we are also investigating more efficient ways to generate energy, including cogeneration and use of renewable fuels such as plant material, or biomass. We are also pursuing alternative raw materials for PLA. Using fermentable sugars from corn stover would allow a second crop to be harvested from the same land used to grow corn grain. PLA can also be derived from wheat, beets and other crops best suited to particular climates.

CANDY WRAPPERS are just one of the products that companies plan to manufacture from Cargill Dow's new plant-based plastic when it hits the market in late 2001.

CARGILL DOW

fossil fuels used to make plastics from renewable raw materials (corn) must be burned to generate energy, whereas the petrochemical processes incorporate a significant portion of the fossil resource into the final product.

Burning more fossil fuels exacerbates an established global climate problem by increasing emissions of greenhouse gases, such as carbon dioxide [see "Is Global Warming Harmful to Health?" by Paul R. Epstein, on page 50]. Naturally, other emissions associated with fossil energy, such as sulfur dioxide, are also likely to increase. This gas contributes to acid rain and should be viewed with concern. What is more, any manufacturing process that increases such emissions stands in direct opposition to the Kyoto Protocol, an international effort led by the United Nations to improve air quality and curtail global warming by reducing carbon dioxide and other gases in the atmosphere.

The conclusions from our analyses were inescapable. The environmental benefit of growing plastic in plants is overshadowed by unjustifiable increases in energy consumption and gas emissions. PLA seems to be the only plant-based plastic that has a chance of becoming competitive in this regard. Though perhaps not as elegant a solution as making PHA in plants, it takes advantage of major factors contributing to an efficient process: low energy requirements and high conversion yields (almost 80 percent of each kilogram of plant sugar used ends up in the final plastic product). But despite the advantages of PLA over other plant-based plastics, its production will inevitably emit more greenhouse gases than do many of its petrochemical counterparts.

The Answer: Renewable Energy

As sobering as our initial analyses were, we did not immediately assume that these plant-based technologies were doomed forever. We imagined that burning plant material, or biomass, could offset the additional energy requirement. Emissions generated in this way can be viewed more favorably than the carbon dioxide released by burning fossil carbon, which has been trapped underground for millions of years. Burning the carbon contained in corn stalks and other plants would not increase net carbon dioxide in the atmosphere, because new plants growing the following spring would, in theory, absorb an equal amount of the gas. (For the same reason, plant-based plastics do not increase carbon dioxide levels when they are incinerated after use.)

We and other researchers reasoned that using renewable biomass as a primary energy source in the corn-processing industry would uncouple the production of plastics from fossil resources, but such a shift would require hurdling some lingering technological barriers and building an entirely new power-generation infrastructure. Our next question was, "Will that ever happen?" Indeed, energy-production patterns in corn-farming states show the exact opposite trend. Most of these states drew a disproportionate amount of their electrical energy from coal—86 percent in Iowa, for example, and 98 percent in Indiana—compared with a national average of around 56 percent in 1998. (Other states derive more of their energy from sources such as natural gas, oil and hydroelectric generators.)

Both Monsanto and Cargill Dow have been looking at strategies for deriving energy from biomass. In its theoretical analysis, Monsanto burned all the corn stover that remained after extraction of the plastic to generate electricity and steam. In this scenario, biomass-derived electricity was more than sufficient to power PHA extraction. The excess energy could be exported from the PHA-extraction facility to replace some of the fossil fuel burned at a nearby electric power facility, thus reducing overall greenhouse gas emissions while producing a valuable plastic.

Interestingly, it was switching to a plant-based energy source—not using plants as a raw material—that generated the primary environmental benefit. Once we considered the production of plastics and the production of energy separately, we saw that a rational scheme would dictate the use of renewable energy over fossil energy for many industrial processes, regardless of the approach to making plastics. In other words, why worry about supplying energy to a process that inherently requires more energy when we have the option of making conventional plastics with much less energy and therefore fewer greenhouse gas emissions? It appears that both emissions and the depletion of fossil resources would be abated by continuing to make plastics from oil while substituting renewable biomass as the fuel.

We did not immediately assume that these plant-based technologies were doomed forever.

Unfortunately, no single strategy can overcome all the environmental, technical and economic limitations of the various manufacturing approaches. Conventional plastics require fossil fuels as a raw material; PLA and PHA do not. Conventional plastics provide a broader range of material properties than PLA and PHA, but they are not biodegradable. Biodegradability helps to relieve the problem of solid-waste disposal, but degradation gives off greenhouse gases, thereby compromising air quality. Plant-based PLA and PHA by fermentation are technologically simpler to produce than PHA grown in corn, but they compete with other needs for agricultural land. And although PLA production uses fewer fossil resources than its petrochemical counterparts, it still requires more energy and thus emits more greenhouse gases during manufacture.

The choices that we as a society will make ultimately depend on how we prioritize the depletion of fossil resources, emissions of greenhouse gases, land use, solid-waste disposal and profitability—all of which are subject to their own interpretation, political constituencies and value systems. Regardless of the particular approach to making plastics, energy use and the resulting emissions constitute the most significant impact on the environment.

In light of this fact, we propose that any scheme to produce plastics should not only reduce greenhouse gas emissions but should also go a step beyond that, to reverse the flux of carbon into the atmosphere. To accomplish this goal will require finding ways to produce *non*degradable plastic from resources that absorb carbon dioxide from the atmosphere, such as plants. The plastic could then be buried after use, which would sequester the carbon in the ground instead of returning it to the atmosphere. Some biodegradable plastics may also end up sequestering carbon, because landfills, where many plastic products end up, typically do not have the proper conditions to initiate rapid degradation.

In the end, reducing atmospheric levels of carbon dioxide may be too much to ask of the plastics industry. But any manufacturing process, not just those for plastics, would benefit from the use of renewable raw materials *and* renewable energy. The significant changes that would be required of the world's electrical power infrastructure to make this shift might well be worth the effort. After all, renewable energy is the essential ingredient in any comprehensive scheme for building a sustainable economy, and as such, it remains the primary barrier to producing truly "green" plastics. SA

The Authors

TILLMAN U. GERNGROSS and STEVEN C. SLATER have each worked for more than eight years in industry and academia to develop technologies for making biodegradable plastics. Both researchers have contributed to understanding the enzymology and genetics of plastic-producing bacteria. In the past two years, they have turned their interests toward the broader issue of how plastics manufacturing affects the environment. Gerngross is an assistant professor at Dartmouth College, and Slater is a senior researcher at Cereon Genomics, a subsidiary of Monsanto, in Cambridge, Mass.

Further Information

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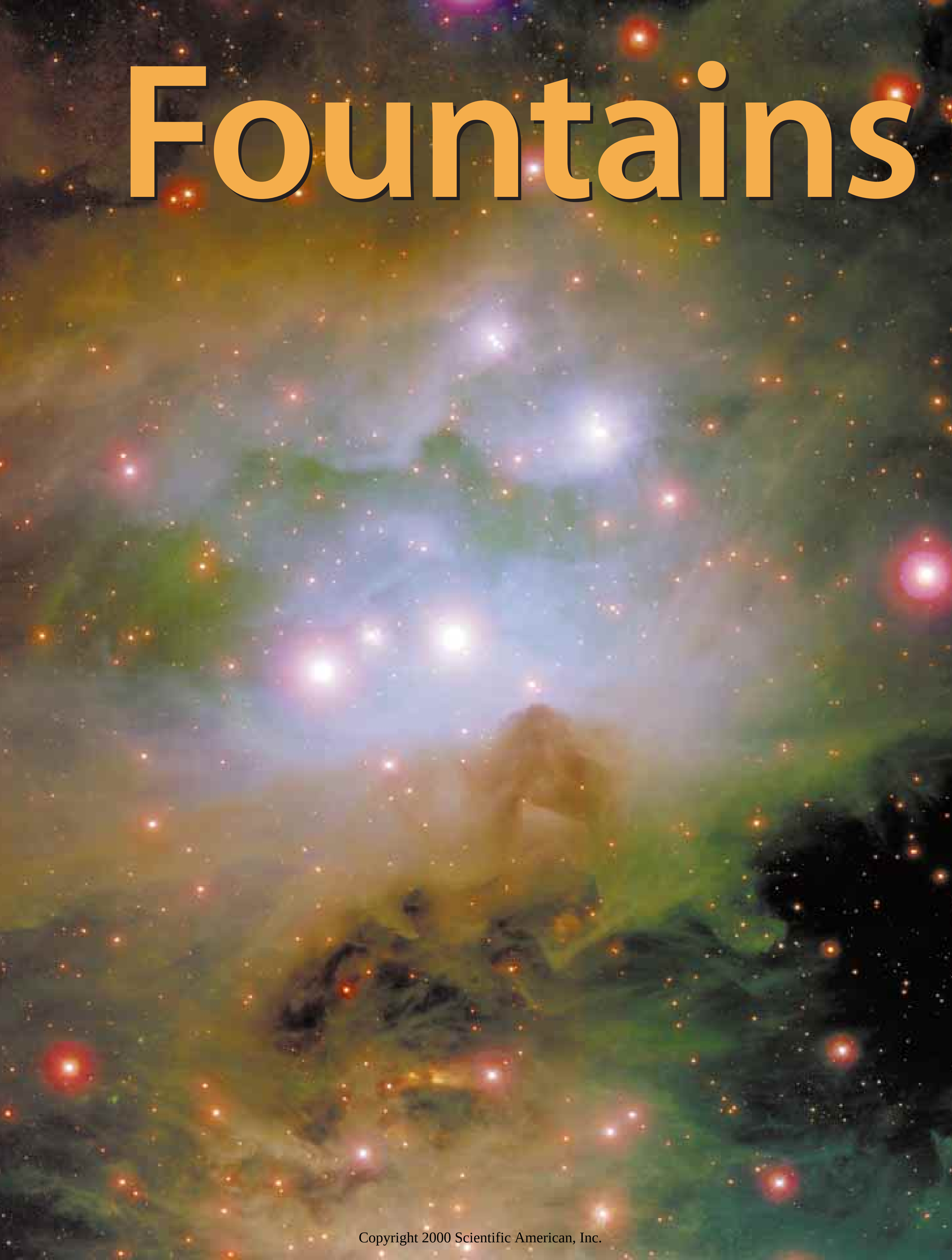
Fountains



# of Youth
Early Days in the Life of a Star

To make a star, gas and dust must fall inward. So why do astronomers see stuff streaming outward?

by Thomas P. Ray

Go out on a winter's night in the Northern Hemisphere and look due south around midnight. You will see the constellation of Orion the Hunter, probably the best-known group of stars after the Big Dipper. Just below Orion's Belt, which is clearly marked by three prominent stars in a line, is the Sword of Orion, and in the center of the sword is a faint fuzzy patch. This region, the Orion Nebula, is a giant stellar nursery embracing thousands of newborn stars.

Orion is a convenient place to study the birth of stars because it is relatively close by—a mere 1,500 light-years away—and has a good mix of low- and high-mass stars. It also contains a vast quantity of gas and dust in the form of a so-called molecular cloud. Such clouds are known to provide the raw material for new stars. What is now happening in Orion probably replicates what took place in our part of the galaxy five billion years ago, when the sun and its planets first came into being.

Understanding how stars and planets form is one of astronomy's quintessential subjects yet, until recently, one of the most poorly understood. Twenty years ago astronomers knew more about the first three minutes of the universe than they did about the first three billion days of our solar system. Only in the past decade have they started to get answers. Infant stars, it turns out, look like scaled-down versions of the heart of a quasar, with powerful jets of material flung outward by sweeping magnetic fields. These stellar fountains of youth not only make for spectacular pictures but also help to resolve paradoxes that have long dogged astronomers.

The Journeywork of the Stars

The theory of how stars and planets form has a venerable history. Just over 200 years ago French mathematician Pierre-Simon Laplace put forward the idea that the solar system was created from a spinning cloud of gas. He proposed that gravity pulled most of the gas to the center, thereby creating the sun. At the same time, some of the material, because of its spin, could not be absorbed by the young sun and instead settled into a disk. Eventually these dregs became the planets. According to modern numerical simulations of the process, once the spinning cloud starts to collapse, it proceeds quickly to the formation of one or more stars, a protoplanetary disk, and a leftover envelope of gas (individual atoms and molecules) and dust (clumps of atoms and molecules) [see "The Early Life of Stars," by Steven W. Stahler; Scientific American, July 1991].

Laplace's model was not universally accepted. Rival theories, such as the idea that the planets were made of material torn from the sun by a passing star, were openly considered up to a few decades ago. The uncertainty was mainly observational: testing the model was well be-

STELLAR BIRTHING GROUND in the Orion Nebula (*opposite page*) has given rise to hundreds of new stars. Surrounding it is an invisible but immense molecular cloud—a million suns' worth of dust and gas in a volume 300 light-years across. Young stars in Orion are swaddled in disks of material about the size of our solar system (*above*); around some, planets may even now be forming.

C. ROBERT O'DELL, MARK McCAUGHREAN AND JOHN BALLY *Hubble Space Telescope* AND NASA (*disks*); GARY BERNSTEIN AND MEGAN C. NOVICKI *University of Michigan* AND LUCENT TECHNOLOGIES (*nebula*)

From Mud to a Star

A star begins to coalesce when a disturbance, such as a nearby supernova explosion, causes a cloud of gas and dust to collapse.

Gas and dust clumps at the center, surrounded by an envelope of material and a swirling disk. Magnetic forces direct jets along the axis.

Material continues to rain onto the disk. Roughly a tenth of it streams out in an uneven flow, shoving aside ambient gas.

yond the astronomical capabilities of, say, 30 years ago, for two reasons. First, the leftover cloud of gas and dust blocks our view of the very region that must be studied. Second, protoplanetary disks subtend minute angles on the sky: if the distance between the sun and Pluto (six billion kilometers) is representative of the scale of the disks, conventional ground-based telescopes can resolve them to a distance of only 200 light-years. Simply building bigger telescopes does not help, because the blurring of detail occurs in the atmosphere.

Theoretical problems also stymied astronomers. Sunlike stars at the youthful age of 100,000 years rotate once every few days and are four or five times bigger than the mature sun. As such stars contract, they should spin faster, just like ice skaters pulling in their arms. Yet the sun has evidently slowed down, currently taking a month to rotate once. Something must have drained away its angular momentum. But what?

Another puzzle is how molecular clouds survive for as long as they do. Gravity is trying to force them to collapse, and without support they should implode within about a million years. In practice, however, clouds seem to have endured for a few tens of millions of years. What holds them up? Thermal pressure is woefully inadequate because the clouds are far too cold, just 10 or 20 kelvins. Turbulence might do the trick, but what would generate it? In giant molecular clouds such as Orion, winds and shock waves produced by embedded massive stars would stir things up, but many smaller, sedate clouds have no massive stars.

The first observational obstacle yielded in the late 1970s, when astronomers began to observe star-forming regions at wavelengths that penetrate the dust shroud. Although dust grains absorb visible light, they have little effect on wavelengths that are much bigger than the grains, which are about one micron across. Studying regions such as the Orion molecular cloud at millimeter wavelengths—a previously unexplored part of the spectrum sandwiched between the infrared and radio bands—astronomers identified dense, cold clumps typically measuring a light-year across. Such clumps, known as molecular cores, contain as much as a few suns' worth of gas and quickly became identified with Laplace's spinning clouds.

As is often the case in astronomy, new mysteries immediately emerged. Although a few of the molecular cores seem to be in the process of collapsing, most of them are stabilized by means that are not entirely understood. What triggers their eventual collapse is equally uncertain, but it may involve some outside push from, for example, a nearby supernova explosion. The biggest conundrum of all concerns the direction in which material is moving. According to Laplace's hypothesis, stars arise from gravitational accretion, so astronomers expected to see signs of gas plummeting toward the cores.

To their astonishment, they discovered that gas, in the form of molecules (as opposed to atoms or ions), is actually moving outward. Usually two giant lobes of molecular gas were found lying on either side of a young star. These lobes, typically a few light-years in length, have masses similar to or even larger than that of the young star itself, and they move apart at speeds of tens of kilometers per second [see "Energetic Outflows from Young Stars," by Charles J. Lada; Scientific American, July 1982].

Jetting from the Crib

The molecular lobes bear a strange resemblance to the vastly larger lobes of hot plasma seen near active galaxies such as quasars. Astronomers had known for years that jets produce these lobes. Squirting outward at velocities close to the speed of light, jets from active galaxies can stretch for many millions of light-years [see "A New Look at Quasars," by Michael Disney; Scientific American, June 1998]. Might a miniature version of these jets also drive the molecular lobes in star-forming regions?

This idea harked back to a discovery in the early 1950s by astronomers George H. Herbig and Guillermo Haro. Herbig, then working at Lick Observatory in northern California, and Haro, at Tonantzintla Observatory in Mexico, independently found some faint fuzzy patches in Orion. Now known as Herbig-Haro objects, these small clouds were initially thought to be sites of star formation. (Some popular astronomy books repeat this erroneous theory even to the present day.) In 1975, however, Richard D. Schwartz, then at the University of California at Santa Cruz, realized that the spectrum of a Herbig-Haro object closely resembles that of the material left over from a supernova. From the Doppler shifting of the spec-

Disk material agglomerates into planetesimals. The envelope and the jets dissipate. By this point, one million years have passed.

The high pressure and temperature at the center of the star trigger nuclear fusion. The planetesimals have assembled into planets.

ALFRED T. KAMAJIAN

tral lines, he found that Herbig-Haro objects are moving at speeds up to a few hundred kilometers per second.

That is slower than the motion of a typical supernova remnant, but Schwartz reckoned that the principles are the same—namely, that the Herbig-Haro objects are heated gas flowing away from a star. The heat, as in supernova remnants, comes from the motion of the gas itself; shock waves convert some of the bulk kinetic energy into thermal energy and then into radiation. Schwartz's idea gained further support when astronomers looked at photographs of Herbig-Haro objects taken a number of years apart. They were indeed moving. By extrapolating backward in time, astronomers deduced the source of Herbig-Haro objects. Invariably it was a star only a few hundred thousand years old.

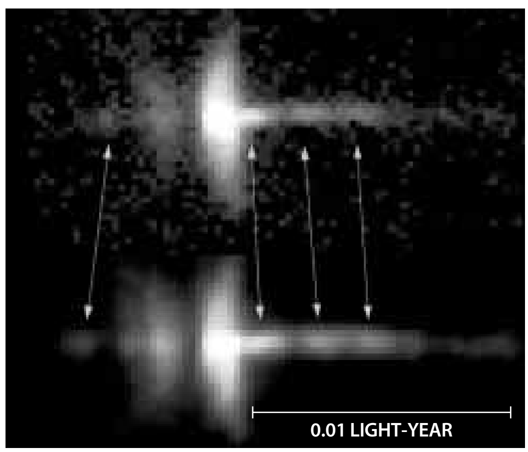
Verification of this connection came with another technological revolution: the charge-coupled device (CCD), the light-sensitive chip found in camcorders and digital cameras. For astronomers, CCDs offer greater sensitivity and contrast than the traditional photographic plates. In 1983 Reinhard Mundt and Josef Fried of the Max Planck Institute for Astronomy in Heidelberg, Germany, made the first CCD observations of stellar jets. Subsequent work by Mundt, Bo Reipurth of the European Southern Observatory in Santiago, Chile, and others (including me) showed that jets from young stars stretch for several light-years. They are closely related to Herbig-Haro objects. In fact, some such objects turned out to be nothing more than the brightest parts of jets. Others were discovered to be bow shocks caused by jets as they plow their way supersonically through ambient gas, like the shock wave that surrounds a bullet zinging through the air. The jets typically have a temperature of about 10,000 kelvins and contain 100 atoms per cubic centimeter—denser than their surroundings but still thinner by a factor of 10,000 than the best vacuum available in labs on the earth. Near the star the jets are narrow, opening with an angle of a few degrees, but farther from the star they fan out, reaching a diameter wider than the orbit of Pluto.

Out of the Way

How are the jets and Herbig-Haro objects, which are mostly made up of atoms and ions, related to the molecular flows? When molecular flows were first discovered, researchers suggested that they might consist of gas that had been accelerated close to the young star. But this idea had its difficulties. Molecular flows, even those associated with low-mass stars, often contain several solar masses of gas. If this amount of material had to be gravitationally sucked in before being accelerated away again, star formation would be an extremely inefficient process. A more persuasive explanation is that a molecular lobe consists of ambient gas that got in the way of the jet and was accelerated.

None of these observations got to the heart of the matter: the disk around the nascent star. Astronomers had long been gathering circumstantial evidence for disks. In the early 1980s the Infrared Astronomical Satellite discovered that many new stars had excess infrared radiation over and above what should be produced by the star alone. Warm dust in a disk seemed the most likely source. Around the same time, millimeter-wave telescopes began to measure the mass of gas and dust around these stars, typically finding 0.01 to 0.1 solar mass—just the right amount of material needed to form planetary systems. In the mid-1980s Edward B. Churchwell of the University of Wisconsin and his colleagues observed the Orion Nebula at radio wavelengths. They found sources comparable in size to our own solar system and suggested that they were clouds of hot gas that had evaporated from a disk.

Sighting the disks themselves, however, ran up against the second observational obstacle: their comparatively small size. For that, astronomers had to await the clarity afforded by the Hubble Space Telescope and by ground-based instruments equipped with adaptive optics. In 1993 C. Robert O'Dell of Rice University and his collaborators observed Orion with Hubble and finally saw the disks that Laplace had predicted [*see illustrations on page 43*]. Their material, where buffeted by the intense radiation and winds from nearby massive stars, was seen to be evaporating. O'Dell christened these disks "proplyds," for protoplanetary disks. The name may actually be a misnomer, because these disks will evaporate within a million years, probably before planets can form.

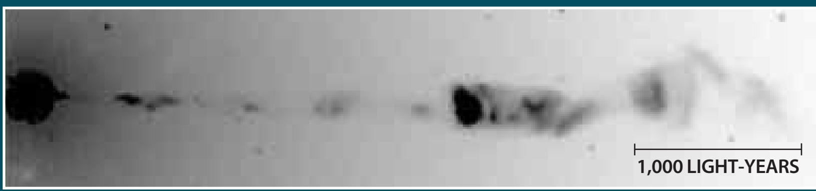


TIME-LAPSE PHOTOGRAPHS of a hatchling star, Herbig-Haro 30, taken a year apart show pockets of gas moving away from the center. These jets are clearly perpendicular to the dark disk that hides the star.

CHRISTOPHER J. BURROWS *Space Telescope Science Institute* AND NASA

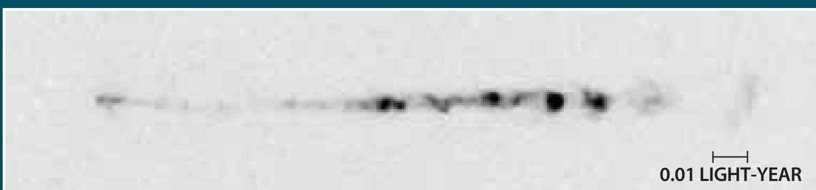
Jet Action

Mysterious though their detailed mechanisms may be, jets always involve the same basic physical process: a balance of power between gravity and angular momentum. Gravity tries to pull matter toward the center of mass, but because of centrifugal forces, the best it can do is gather material into a swirling disk. Narrow streams of gas shoot out along the axis of rotation, the direction in which matter can most easily move. The escaping matter carries away angular momentum, thereby allowing less footloose matter to settle inward.



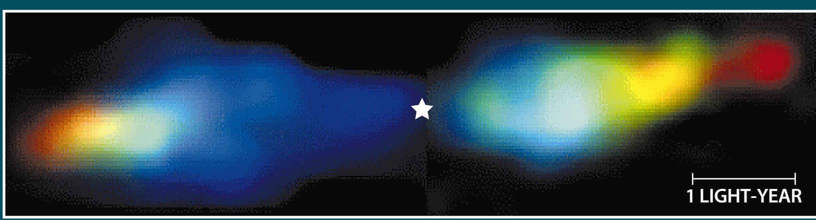
WILLIAM B. SPARKS *Space Telescope Science Institute*

In the core of the active galaxy Messier 87, the driving force is thought to be a black hole a billion times more massive than the sun.



THOMAS P. RAY

On a much smaller scale, a newborn star whips up and sprays out a current of gas known as Herbig-Haro 34. The jet may push ambient molecular gas outward.



MICHEL FICH *University of Waterloo* AND GERALD MORIARTY-SCHIEVEN *Joint Astronomy Center, Hawaii*

Observing the star-forming region NGC 2264 at millimeter wavelengths, astronomers see two lobes of molecular gas moving at tens of kilometers per second. Red indicates the fastest velocities, violet the slowest.

JON A. MORSE *Space Telescope Science Institute* AND NASA

Complex jet patterns, as evident in Herbig-Haro 47, can arise because of variations in the outflow rate and the gravitational effect of companion stars.

But similar disks in milder environments should indeed survive long enough to give birth to planets.

With the discovery of all the basic components of the modern version of Laplace's theory—spinning clouds, outflows, disks—astronomers could begin to study the relationships among them. My colleagues and I, along with another group led by Christopher J. Burrows of the Space Telescope Science Institute, turned Hubble on Herbig-Haro 30, which consists of a pair of oppositely directed jets. To our surprise, the images revealed two small cusp-shaped nebulae where the source of the jets should be. Cutting across the nebulae is a dark band. It soon became clear that we were looking at a disk perpendicular to the jets. As seen from our edge-on view, the disk obscures the central star. The nebulae are dust clouds illuminated by starlight. Jets stream outward, culminating in the Herbig-Haro objects. The jigsaw puzzle of star formation was coming together.

In active galaxies, disks are crucial to the formation of jets. But how does this process work for an embryonic star? An intriguing coincidence has provided a crucial clue. All the jets and flows located near Herbig-Haro 30, with one odd exception, have roughly the same orientation. In fact, they are aligned with the magnetic field of the parent cloud. This seems to support ingenious suggestions—made by Ralph E. Pudritz and Colin A. Norman, both then at the University of Cambridge, and by Frank H. Shu of the University of California at Berkeley—for how magnetic fields could drive an outflow from a young star.

Astronomy abounds with examples of magnetic fields guiding ionized gas. For example, auroras are caused by charged particles that stream down the earth's magnetic field lines and hit the upper atmosphere. In the same way, ionized particles from a circumstellar disk could attach themselves to the field lines of either the disk or the star. Because the disk is spinning, the particles would experience a centrifugal force and would thus be flung out along the field lines. More matter would flow in to replace what was lost, and so the process would continue. Although most of the matter would end up being accreted by the star, some 10 percent might be ejected. In computer simulations the process proceeds in fits and starts, which would account for the knotty structures seen in many jets.

Nebulous No More

The realization that jets are integral to star formation may solve several of the theoretical puzzles. As particles travel outward, they carry angular momentum away from their source—which would partially explain why mature stars such as the sun rotate so slowly. Jets may also churn up the surrounding cloud, supplying the necessary turbulent support to slow down its collapse.

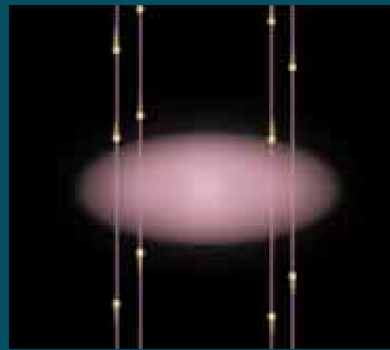
At the same time, many questions remain. For example, only about 50 percent of optically visible young stars are found to have disks. The other stars presumably had disks as well, but these disks may have already coalesced into planets. Observers, however, have been unable to confirm this. Another problem in star formation is the distribution of stellar masses. Why is the ratio of high- to low-mass stars pretty much the same irrespective of location in the galaxy? This ratio seems to be a fundamental property of the way molecular clouds fragment, but for unknown reasons. On a related note, researchers know little about the early life of high-mass stars—partly because they are rarer, partly because they evolve faster and are difficult to catch in the act of forming.

With these caveats, astronomers can now sketch out nature's recipe for stars. They form in interstellar clouds that consist largely of the ashes of earlier generations of stars. The dust was manufactured in the cool winds and outer atmospheres of stars as they approached the ends of their lives. The clouds are also laced with heavy elements such as iron and oxygen that were forged deep in the nuclear furnaces of bygone stars. Magnetic fields or turbulent motions hold up the clouds, but eventually they collapse under their own weight, perhaps because the magnetic fields leak away, the turbulence dissipates or a supernova goes off nearby. As the material falls in, the clouds fragment into cloudlets, each of which settles into a primitive star system. In massive molecular cores, such as those that gave rise to the cluster in the Orion Nebula, these systems are spaced every few light-weeks (as opposed to light-years) apart. Most stars in the galaxy, including the sun, probably formed in such clusters.

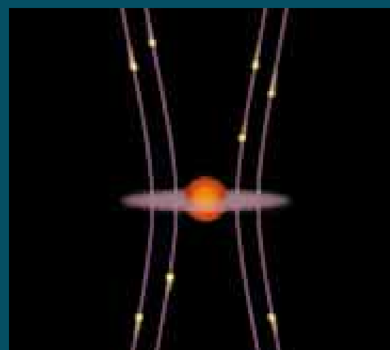
Jets carry away angular momentum and allow the accretion to continue. Our sun must once have had narrow jets that stretched for several light-years. What turned them off is not certain. The store of infalling material may simply have run out. Some of it may have been driven away by the outflows; if so, the jets may have served to limit the sun's final mass. Around the same time, large dust grains were beginning to stick together to form planetesimals, the building blocks of the planets. The planetesimals swept up any remaining gas, further choking off the jets. The outflows from the sun and its stellar contemporaries blew away the leftover gas and dust that threaded the space between them. This weakened the gravitational glue that bound them together, and over a few million years the stars dispersed. Today the nearest star to the sun is about four light-years away.

Two centuries after Laplace put forward his nebular hypothesis, the pieces are beginning to fall into place. Studies of young stars suggest not only that planet formation is going on today but that planets are very common throughout our own and other galaxies. SA

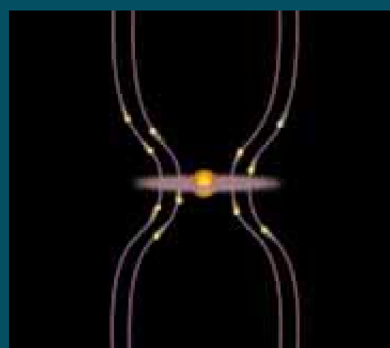
Magnetic, Peripatetic



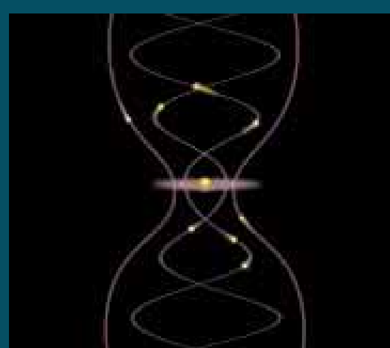
The generation of jets may begin when material—a mixture of ions, atoms, molecules and dust—rains onto the circumstellar disk along magnetic field lines.



As the disk contracts under gravity, the lines (which are frozen into the material) are pulled in, taking on an hourglass shape.



When the field lines are bent to an angle of 30 degrees from the perpendicular, centrifugal force overcomes gravity and flings material outward along the lines.



The inertia of the swirling material twists the field lines into a helix, which helps to channel the outward-flowing material in a vertical direction.

ALFRED T. KAMAJIAN

The Author

THOMAS P. RAY told his high school career adviser that he wanted to become an astronomer. Her reply: "That's a great idea, but what real job would you like?" Today he is gainfully employed as a professor at the Dublin Institute for Advanced Studies, having also worked at the University of Sussex and the Max Planck Institute for Astronomy in Heidelberg, Germany. Ray has been the principal or co-investigator on numerous Hubble observations of jets from young stars. His other interests include quasars, comets, archaeoastronomy (the study of sites such as Stonehenge), sailing and Guinness.

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Is Global Warming Harmful to Health?

Computer models indicate that many diseases will surge as the earth's atmosphere heats up. Signs of the predicted troubles have begun to appear

by Paul R. Epstein

Today few scientists doubt the atmosphere is warming. Most also agree that the rate of heating is accelerating and that the consequences of this temperature change could become increasingly disruptive. Even high school students can reel off some projected outcomes: the oceans will warm, and glaciers will melt, causing sea levels to rise and salt water to inundate settlements along many low-lying coasts. Meanwhile the regions suitable for farming will shift. Weather patterns should also become more erratic and storms more severe.

Yet less familiar effects could be equally detrimental. Notably, computer models predict that global warming, and other climate alterations it induces, will expand the incidence and distribution of many serious medical disorders. Disturbingly, these forecasts seem to be coming true.

Heating of the atmosphere can influence health through several routes. Most directly, it can generate more, stronger and hotter heat waves, which will become especially treacherous if the evenings fail to bring cooling relief. Unfortunately, a lack of nighttime cooling seems to be in the cards; the atmosphere is heating unevenly and is showing the biggest rises at night, in winter and at latitudes higher than about 50 degrees. In some places, the number of deaths related to heat waves is projected to double by 2020. Prolonged heat can, moreover, enhance production of smog and the dispersal of allergens. Both effects have been linked to respiratory symptoms.

Global warming can also threaten human well-being profoundly, if somewhat less directly, by revising weather patterns—particularly by pumping up the frequency and intensity of floods and droughts and by causing rapid swings in the weather. As the atmosphere has warmed over the past century, droughts in arid areas have persisted longer, and massive bursts of precipitation have become more common. Aside from causing death by drowning or starvation, these disasters promote by various means the emergence, resurgence and spread of infectious disease.

That prospect is deeply troubling, because infectious illness is a genie that can be very hard to put back into its bottle. It may kill fewer people in one fell swoop than a raging flood or an extended drought, but once it takes root in a community, it often defies eradication and can invade other areas.

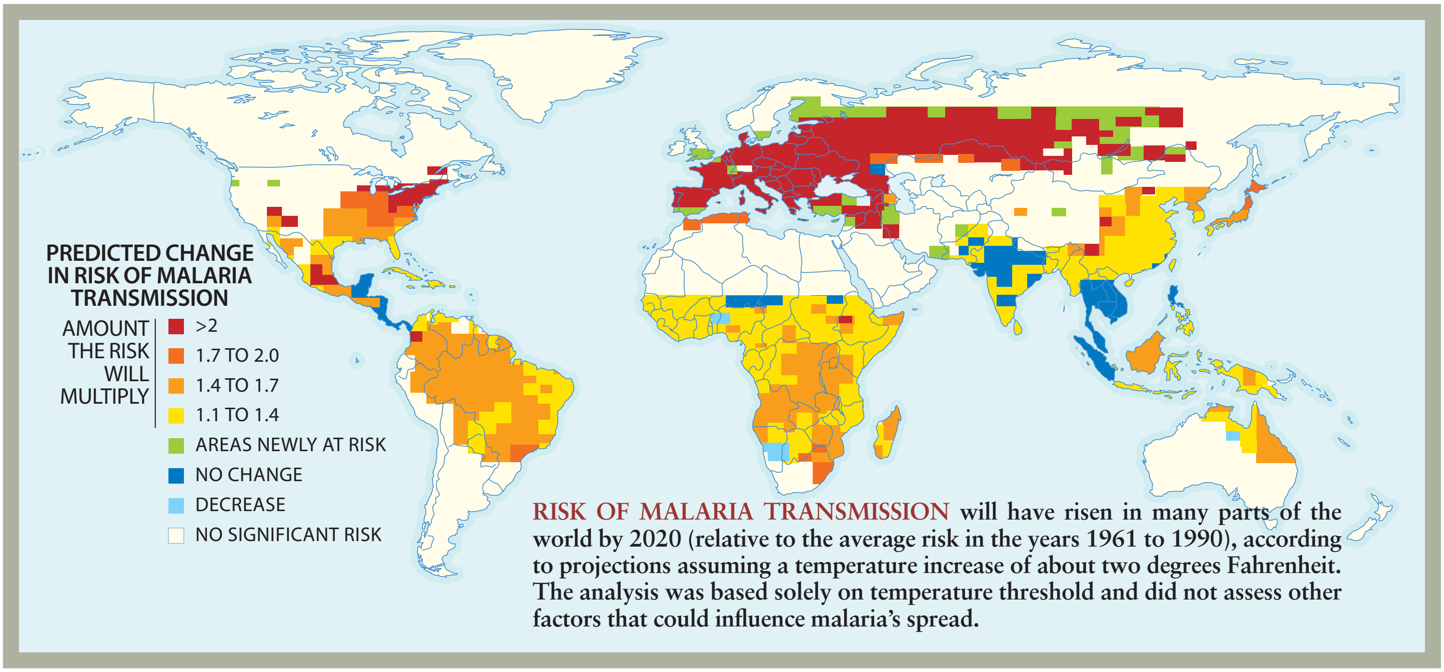
The control issue looms largest in the developing world, where resources for prevention and treatment can be scarce. But the technologically advanced nations, too, can fall victim to surprise attacks—as happened last year when the West Nile virus broke out for the first time in North America, killing seven New Yorkers. In these days of international commerce and travel, an infectious disorder that appears in one part of the world can quickly become a problem continents away if the disease-causing agent, or pathogen, finds itself in a hospitable environment.

Floods and droughts associated with global climate change could undermine health in other ways as well. They could damage crops and make them vulnerable to infection and infestations by pests and choking weeds, thereby reducing food supplies and potentially contributing to malnutrition. And they could permanently or semipermanently displace entire populations in developing countries, leading to overcrowding and the diseases connected with it, such as tuberculosis.

Weather becomes more extreme and variable with atmospheric heating in part because the warming accelerates the water cycle: the process in which water vapor, mainly from the oceans, rises into the atmosphere before condensing out as precipitation. A warmed atmosphere heats the oceans (leading to faster

JEAN-MARC BOUJU *AP Photo (above and far right)*; KAREL PRINSLOO *AP Photo (right)*

WOMAN RINSES RICE in floodwaters outside her hut in Madagascar. Heavy floods earlier this year there and to the west in Mozambique led to outbreaks of cholera (a waterborne disease) and malaria (transmitted by mosquitoes). At the right, a mother in Mozambique holds her child, who is feared to have malaria; at the far right, the body of a cholera victim in Madagascar is placed in a coffin. As global warming increases, it is expected to generate more frequent and devastating floods and droughts around the world—and more of the infectious diseases those conditions promote.



RISK OF MALARIA TRANSMISSION will have risen in many parts of the world by 2020 (relative to the average risk in the years 1961 to 1990), according to projections assuming a temperature increase of about two degrees Fahrenheit. The analysis was based solely on temperature threshold and did not assess other factors that could influence malaria's spread.

BRYAN CHRISTIE; SOURCE: PIM MARTENS *Maastricht University*

evaporation), and it holds more moisture than a cool one. When the extra water condenses, it more frequently drops from the sky as larger downpours. While the oceans are being heated, so is the land, which can become highly parched in dry areas. Parching enlarges the pressure gradients that cause winds to develop, leading to turbulent winds, tornadoes and other powerful storms. In addition, the altered pressure and temperature gradients that accompany global warming can shift the distribution of when and where storms, floods and droughts occur.

I will address the worrisome health effects of global warming and disrupted climate patterns in greater detail, but I should note that the consequences may not all be bad. Very high temperatures in hot regions may reduce snail populations, which have a role in transmitting schistosomiasis, a parasitic disease. High winds may at times disperse pollution. Hotter winters in normally chilly areas may reduce cold-related heart attacks and respiratory ailments. Yet overall, the undesirable effects of more variable weather are likely to include new stresses and nasty surprises that will overshadow any benefits.

Mosquitoes Rule in the Heat

Diseases relayed by mosquitoes—such as malaria, dengue fever, yellow fever and several kinds of encephalitis—are among those eliciting the greatest concern as the world warms. Mosquitoes acquire disease-causing microorganisms when they take a blood meal from an infected animal or person. Then the pathogen reproduces inside the insects, which may deliver disease-causing doses to the next individuals they bite.

Mosquito-borne disorders are projected to become increasingly prevalent because their insect carriers, or "vectors," are very sensitive to meteorological conditions. Cold can be a friend to humans, because it limits mosquitoes to seasons and regions where temperatures stay above certain minimums. Winter freezing kills many eggs, larvae and adults outright. *Anopheles* mosquitoes, which transmit malaria parasites (such as *Plasmodium falciparum*), cause sustained outbreaks of malaria only where temperatures routinely exceed 60 degrees Fahrenheit. Similarly, *Aedes aegypti* mosquitoes, responsible for yellow fever and dengue fever, convey virus only where temperatures rarely fall below 50 degrees F.

Excessive heat kills insects as effectively as cold does. Nevertheless, within their survivable range of temperatures, mosquitoes proliferate faster and bite more as the air becomes warmer. At the same time, greater heat speeds the rate at which pathogens inside them reproduce and mature. At 68 degrees F, the immature *P. falciparum* parasite takes 26 days to develop fully, but at 77 degrees F, it takes only 13 days. The *Anopheles* mosquitoes that spread this malaria parasite live only several weeks; warmer temperatures raise the odds that the parasites will mature in time for the mosquitoes to transfer the infection. As whole areas heat up, then, mosquitoes could expand into formerly forbidden territories, bringing illness with them. Further, warmer nighttime and winter temperatures may enable them to cause more disease for longer periods in the areas they already inhabit.

The extra heat is not alone in encouraging a rise in mosquito-borne infections. Intensifying floods and droughts resulting from global warming can each help trigger outbreaks by creating breeding grounds for insects whose dessicated eggs remain viable and hatch in still water. As floods recede, they leave puddles. In times of drought, streams can become stagnant pools, and people may put out containers to catch water; these pools and pots, too, can become incubators for new mosquitoes. And the insects can gain another boost if climate change or other processes (such as alterations of habitats by humans) reduce the populations of predators that normally keep mosquitoes in check.

Mosquitoes on the March

Malaria and dengue fever are two of the mosquito-borne diseases most likely to spread dramatically as global temperatures head upward. Malaria (marked by chills, fever, aches and anemia) already kills 3,000 people, mostly children, every day. Some models project that by the end of the 21st century, ongoing warming will have enlarged the zone of potential malaria transmission from an area containing 45 percent of the world's population to an area containing about 60 percent. That news is bad indeed, considering that no vaccine is available and that the causative parasites are becoming resistant to standard drugs.

True to the models, malaria is reappearing north and south of the tropics. The U.S. has long been home to *Anopheles* mosquitoes, and malaria circulated here decades ago. By the 1980s mosquito-control programs and other public health measures had restricted the disorder to California. Since 1990, however, when the hottest decade on record began, outbreaks of locally transmitted malaria have occurred during hot spells in Texas, Florida, Georgia, Michigan, New Jersey and New York (as well as in Toronto). These episodes undoubtedly started with a traveler or stowaway mosquito carrying malaria parasites. But the parasites clearly found friendly conditions in the U.S.—enough warmth and humidity, and plenty of mosquitoes able to transport them to victims who had not traveled. Malaria has returned to the Korean peninsula, parts of southern Europe and the former Soviet Union and to the coast of South Africa along the Indian Ocean.

Dengue, or "breakbone," fever (a severe flulike viral illness that sometimes causes fatal internal bleeding) is spreading as well. Today it afflicts an estimated 50 million to 100 million in the tropics and subtropics (mainly in urban areas and their surroundings). It has broadened its range in the Americas over the past 10 years and had reached down to Buenos Aires by the end of the 1990s. It has also found its way to northern Australia. Neither a vaccine nor a specific drug treatment is yet available.

Although these expansions of malaria and dengue fever certainly fit the predictions, the cause of that growth cannot be traced conclusively to global warming. Other factors could have been involved as well—for instance, disruption of the environment in ways that favor mosquito proliferation, declines in mosquito-control and other public health programs, and rises in drug and pesticide resistance. The case for a climatic contribution becomes stronger, however, when other projected consequences of global warming appear in concert with disease outbreaks.

Such is the case in highlands around the world. There, as anticipated, warmth is climbing up many mountains, along with plants and butterflies, and summit glaciers are melting. Since 1970 the elevation at which temperatures are always below freezing has ascended almost 500 feet in the tropics. Marching upward, too, are mosquitoes and mosquito-borne diseases.

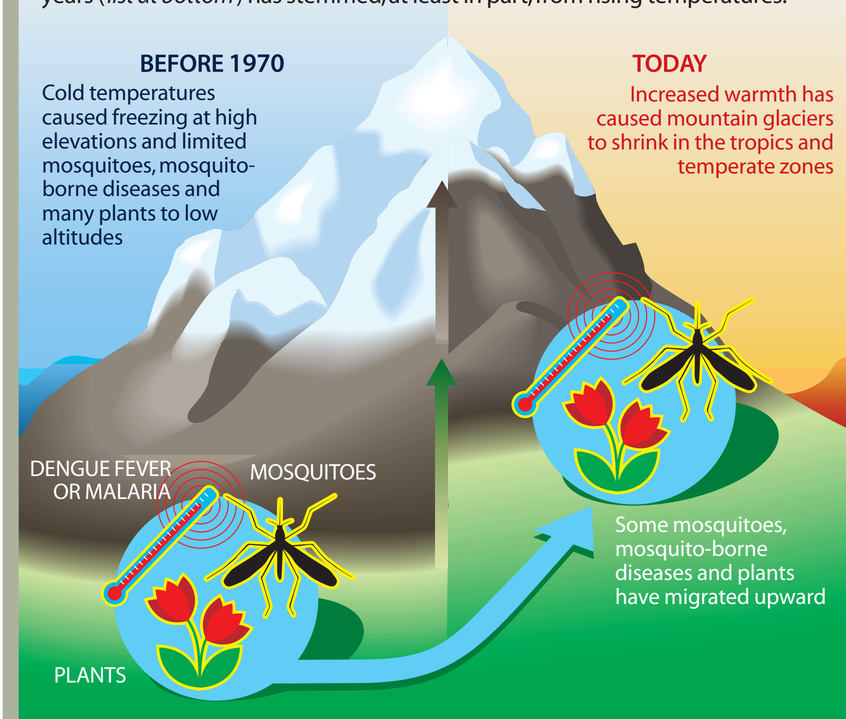
In the 19th century, European colonists in Africa settled in the cooler mountains to escape the dangerous swamp air ("*mal aria*") that fostered disease in the lowlands. Today many of those havens are compromised. Insects and insect-borne infections are being reported at high elevations in South and Central America, Asia, and east and central Africa. Since 1980 *Ae. aegypti* mosquitoes, once limited by temperature thresholds to low altitudes, have been found above one mile in the highlands of northern India and at 1.3 miles in the Colombian Andes. Their presence magnifies the risk that dengue and yellow fever may follow. Dengue fever itself has struck at the mile mark in Taxco, Mexico. Patterns of insect migration change faster in the mountains than they do at sea level. Those alterations can thus serve as indicators of climate change and of diseases likely to expand their range.

Opportunists Like Sequential Extremes

The increased climate variability accompanying warming will probably be more important than the rising heat itself in fueling unwelcome outbreaks of certain vector-borne illnesses. For instance, warm winters followed by hot, dry summers (a pattern that could

Changes Are Already Under Way

Computer models have predicted that global warming would produce several changes in the highlands: summit glaciers (like North Polar sea ice) would begin to melt, and plants, mosquitoes and mosquito-borne diseases would migrate upward into regions formerly too cold for them (*diagram*). All these predictions are coming true. This convergence strongly suggests that the upward expansion of mosquitoes and mosquito-borne diseases documented in the past 15 years (*list at bottom*) has stemmed, at least in part, from rising temperatures.



WHERE DISEASES OR THEIR CARRIERS HAVE REACHED HIGHER ELEVATIONS

Malaria
- Highlands of Ethiopia, Rwanda, Uganda and Zimbabwe
- Usamabara Mountains, Tanzania
- Highlands of Papua New Guinea and West Papua (Irian Jaya)

Dengue fever
- San Jose, Costa Rica
- Taxco, Mexico

***Aedes aegypti* mosquitoes** (can spread dengue fever and yellow fever)
- Eastern Andes Mountains, Colombia
- Northern highlands of India

BRYAN CHRISTIE

become all too familiar as the atmosphere heats up) favor the transmission of St. Louis encephalitis and other infections that cycle among birds, urban mosquitoes and humans.

This sequence seems to have abetted the surprise emergence of the West Nile virus in New York City last year. No one knows how this virus found its way into the U.S. But one reasonable explanation for its persistence and amplification here centers on the weather's effects on *Culex pipiens* mosquitoes, which accounted for the bulk of the transmission. These urban dwellers typically lay their eggs in damp basements, gutters, sewers and polluted pools of water.

The interaction between the weather, the mosquitoes and the virus probably went something like this: The mild winter of 1998–99 enabled many of the mosquitoes to survive into the spring, which arrived early. Drought in spring and summer concentrated nourishing organic matter in their breeding areas and simultaneously killed off mosquito predators, such as lacewings and ladybugs, that would otherwise have helped limit mosquito populations. Drought would also have led birds to congregate more, as they shared fewer and smaller watering holes, many of which were frequented, naturally, by mosquitoes.

Once mosquitoes acquired the virus, the heat wave that accompanied the drought would speed up viral maturation inside the insects. Consequently, as infected mosquitoes sought blood meals, they could spread the virus to birds at a rapid clip. As bird after bird became infected, so did more mosquitoes, which ultimately fanned out to infect human beings. Torrential rains toward the end of August provided new puddles for the breeding of *C. pipiens* and other mosquitoes, unleashing an added crop of potential virus carriers.

Like mosquitoes, other disease-conveying vectors tend to be "pests"—opportunists that reproduce quickly and thrive under disturbed conditions unfavorable to species with more specialized needs. In the 1990s climate variability contributed to the appearance in humans of a new rodent-borne ailment: the hantavirus pulmonary syndrome, a highly lethal infection of the lungs. This infection can jump from animals to humans when people inhale viral particles hiding in the secretions and excretions of rodents. The sequential weather extremes that set the stage for the first human eruption, in the U.S. Southwest in 1993, were long-lasting drought interrupted by intense rains.

First, a regional drought helped to reduce the pool of animals that prey on rodents—raptors (owls, eagles, prairie falcons, red-tailed hawks and kestrels), coyotes and snakes. Then, as drought yielded to unusually heavy rains early in 1993, the rodents found a bounty of food, in the form of grasshoppers and piñon nuts. The resulting population explosion enabled a virus that had been either inactive or isolated in a small group to take hold in many rodents. When drought returned in summer, the animals sought food in human dwellings and brought the disease to people. By fall 1993, rodent numbers had fallen, and the outbreak abated.

Subsequent episodes of hantavirus pulmonary syndrome in the U.S. have been limited, in part because early-warning systems now indicate when rodent-control efforts have to be stepped up and because people have learned to be more careful about avoiding the animals' droppings. But the disease has appeared in Latin America, where some ominous evidence suggests that it may be passed from one person to another.

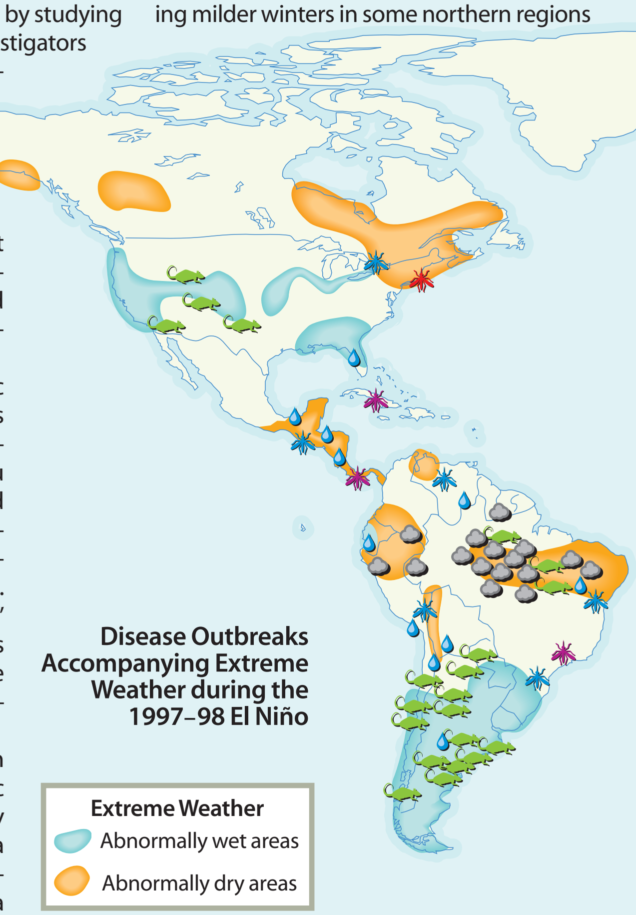
As the natural ending of the first hantavirus episode demonstrates, ecosystems can usually survive occasional extremes. They are even strengthened by seasonal changes in weather conditions, because the species that live in changeable climates have to evolve an ability to cope with a broad range of conditions. But long-lasting extremes and very wide fluctuations in weather can overwhelm ecosystem resilience. (Persistent ocean heating, for instance, is menacing coral reef systems, and drought-driven forest fires are threatening forest habitats.) And ecosystem upheaval is one of the most profound ways in which climate change can affect human health. Pest control is one of nature's underappreci-

El Niño's Message

Scientists often gain insight into the workings of complicated systems by studying subsystems. In that spirit, investigators concerned about global warming's health effects are assessing outcomes of the El Niño/Southern Oscillation (ENSO), a climate process that produces many of the same meteorological changes predicted for a warming world. The findings are not reassuring.

"El Niño" refers to an oceanic phenomenon that materializes every five years or so in the tropical Pacific. The ocean off Peru becomes unusually warm and stays that way for months before returning to normal or going to a cold extreme (La Niña). The name "Southern Oscillation" refers to atmospheric changes that happen in tandem with the Pacific's shifts to warmer or cooler conditions.

During an El Niño, evaporation from the heated eastern Pacific can lead to abnormally heavy rains in parts of South America and Africa; meanwhile other areas of South America and Africa and parts of Southeast Asia and Australia suffer droughts. Atmospheric pressure changes over the tropical Pacific also have ripple effects throughout the globe, generally yielding milder winters in some northern regions



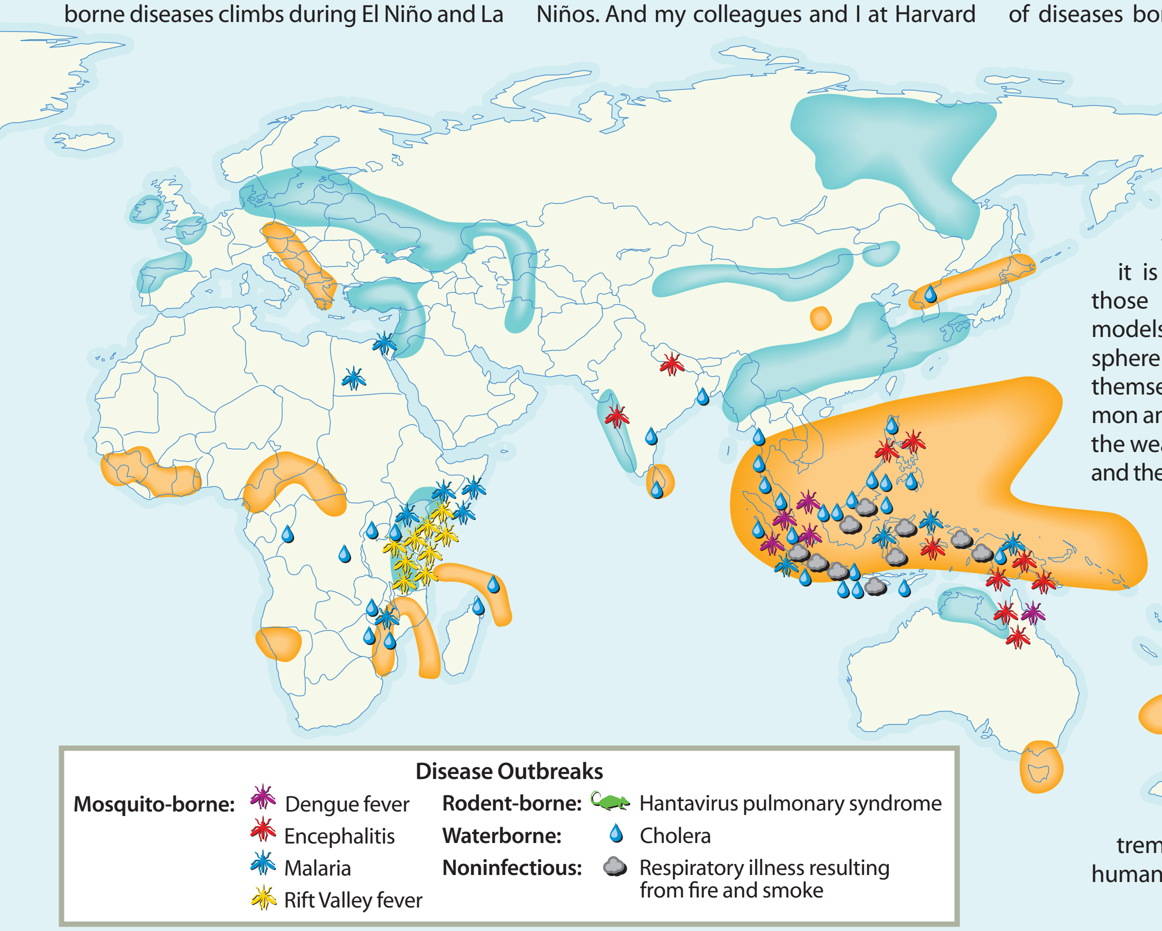
of the U.S. and western Canada. During a La Niña, weather patterns in the affected areas may go to opposite extremes.

The incidence of vector-borne and waterborne diseases climbs during El Niño and La Niña years, especially in areas hit by floods or droughts. Long-term studies in Colombia, Venezuela, India and Pakistan reveal, for instance, that malaria surges in the wake of El Niños. And my colleagues and I at Harvard University have shown that regions stricken by flooding or drought during the El Niño of 1997–98 (the strongest of the century) often had to contend as well with a convergence of diseases borne by mosquitoes, rodents and water (*map*). Additionally, in many dry areas, fires raged out of control, polluting the air for miles around.

ENSO is not merely a warning of troubles to come; it is likely to be an engine for those troubles. Several climate models predict that as the atmosphere and oceans heat up, El Niños themselves will become more common and severe—which means that the weather disasters they produce and the diseases they promote could become more prevalent as well.

Indeed, the ENSO pattern has already begun to change. Since 1976 the intensity, duration and pace of El Niños have increased. And during the 1990s, every year was marked by an El Niño or La Niña extreme. Those trends bode ill for human health in the 21st century.

—P.R.E.



BRYAN CHRISTIE; SOURCES: NOAA CLIMATE PREDICTION CENTER; http://chge2.med.harvard.edu/enso/disease.html

ated services to people; well-functioning ecosystems that include diverse species help to keep nuisance organisms in check. If increased warming and weather extremes result in more ecosystem disturbance, that disruption may foster the growth of opportunist populations and enhance the spread of disease.

Unhealthy Water

Beyond exacerbating the vector-borne illnesses mentioned above, global warming will probably elevate the incidence of waterborne diseases, including cholera (a cause of severe diarrhea). Warming itself can contribute to the change, as can a heightened frequency and extent of droughts and floods. It may seem strange that droughts would favor waterborne disease, but they can wipe out supplies of safe drinking water and concentrate contaminants that might otherwise remain dilute. Further, the lack of clean water during a drought interferes with good hygiene and safe rehydration of those who have lost large amounts of water because of diarrhea or fever.

Floods favor waterborne ills in different ways. They wash sewage and other sources of pathogens (such as *Cryptosporidium*) into supplies of drinking water. They also flush fertilizer into water supplies. Fertilizer and sewage can each combine with warmed water to trigger expansive blooms of harmful algae. Some of these blooms are directly toxic to humans who inhale their vapors; others contaminate fish and shellfish, which, when eaten, sicken the consumers. Recent discoveries have revealed that algal blooms can threaten human health in yet another way. As they grow bigger, they support the proliferation of various pathogens, among them *Vibrio cholerae*, the causative agent of cholera.

Drenching rains brought by a warmed Indian Ocean to the Horn of Africa in 1997 and 1998 offer an example of how people will be affected as global warming spawns added flooding. The downpours set off epidemics of cholera as well as two mosquito-borne infections: malaria and Rift Valley fever (a flulike disease that can be lethal to livestock and people alike).

To the west, Hurricane Mitch stalled over Central America in October 1998 for three days. Fueled by a heated Caribbean, the storm unleashed torrents that killed at least 11,000 people. But that was only the beginning of its havoc. In the aftermath, Honduras reported thousands of cases of cholera, malaria and dengue fever. Beginning in February of this year, unprecedented rains and a series of cyclones inundated large parts of southern Africa. Floods in Mozambique and Madagascar killed hundreds, displaced thousands and spread both cholera and malaria. Such events can also greatly retard economic development, and its accompanying public health benefits, in affected areas for years.

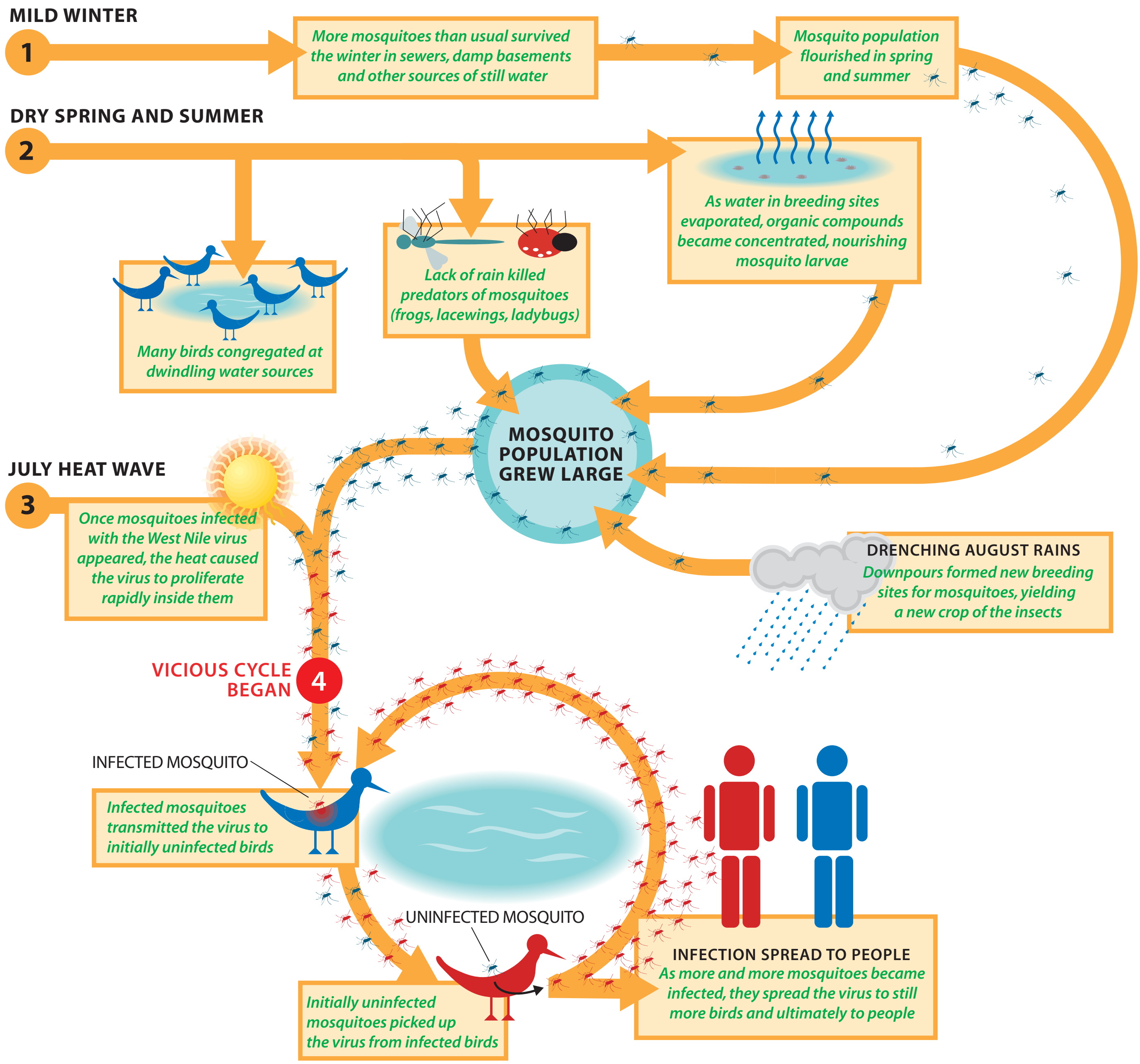
Solutions

The health toll taken by global warming will depend to a large extent on the steps taken to prepare for the dangers. The ideal defensive strategy would have multiple components. One would include improved surveillance systems that would promptly spot the emergence or resurgence of infectious diseases or the vectors that carry them. Discovery could quickly trigger measures to control vector proliferation without harming the environment, to advise the public about self-protection, to provide vaccines (when available) for at-risk populations and to deliver prompt treatments.

This past spring, efforts to limit the West Nile virus in the northeastern U.S. followed this model. On seeing that the virus had survived the winter, public health officials warned people to clear their yards of receptacles that can hold stagnant water favorable to mosquito breeding. They also introduced fish that

Weather and the West Nile Virus

This diagram offers a possible explanation for how a warming trend and sequential weather extremes helped the West Nile virus to establish itself in the New York City area in 1999. Whether the virus entered the U.S. via mosquitoes, birds or people is unknown. But once it arrived, interactions between mosquitoes and birds amplified its proliferation.



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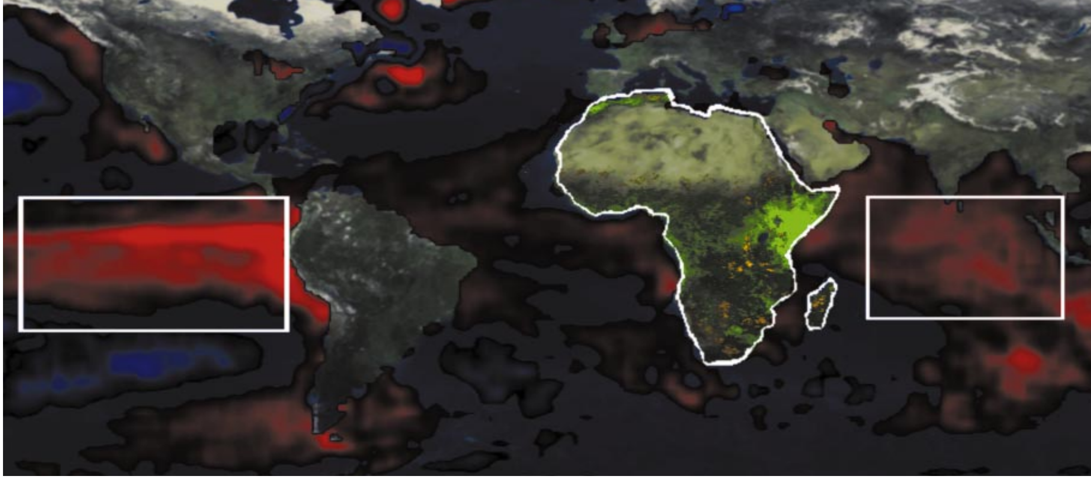
eat mosquito larvae into catch basins and put insecticide pellets into sewers.

Sadly, however, comprehensive surveillance plans are not yet realistic in much of the world. And even when vaccines or effective treatments exist, many regions have no means of obtaining and distributing them. Providing these preventive measures and treatments should be a global priority.



NASA (http://pao.gsfc.nasa.gov/gsfc/earth/rvalley/rvalley.htm)

SATELLITE IMAGE revealed that the sea-surface temperature of both the western equatorial Indian Ocean and the eastern Pacific was warm (*boxes*) and that the Horn of Africa was lush with vegetation (*green*) because of heavy rains. This pattern indicated that the Horn was at risk for an epidemic of Rift Valley fever in livestock and people. Satellite surveillance is being used increasingly to detect conditions conducive to disease outbreaks, so that preventive measures can be taken.

A second component would focus on predicting when climatological and other environmental conditions could become conducive to disease outbreaks, so that the risks could be minimized. If climate models indicate that floods are likely in a given region, officials might stock shelters with extra supplies. Or if satellite images and sampling of coastal waters indicate that algal blooms related to cholera outbreaks are beginning, officials could warn people to filter contaminated water and could advise medical facilities to arrange for additional staff, beds and treatment supplies.

Research reported in 1999 illustrates the benefits of satellite monitoring. It showed that satellite images detecting heated water in two specific ocean regions and lush vegetation in the Horn of Africa can predict outbreaks of Rift Valley fever in the Horn five months in advance. If such assessments led to vaccination campaigns in animals, they could potentially forestall epidemics in both livestock and people.

A third component of the strategy would attack global warming itself. Human activities that contribute to the heating or that exacerbate its effects must be limited. Little doubt remains that burning fossil fuels for energy is playing a significant role in global warming, by spewing carbon dioxide and other heat-absorbing, or "greenhouse," gases into the air. Cleaner energy sources must be put to use quickly and broadly, both in the energy-guzzling industrial world and in developing nations, which cannot be expected to cut back on their energy use. (Providing sanitation, housing, food, refrigeration and indoor fires for cooking takes energy, as do the pumping and purification of water and the desalination of seawater for irrigation.) In parallel, forests and wetlands need to be restored, to absorb carbon dioxide and floodwaters and to filter contaminants before they reach water supplies.

The world's leaders, if they are wise, will make it their business to find a way to pay for these solutions. Climate, ecological systems and society can all recoup after stress, but only if they are not exposed to prolonged challenge or to one disruption after another. The Intergovernmental Panel on Climate Change, established by the United Nations, calculates that halting the ongoing rise in atmospheric concentrations of greenhouse gases will require a whopping 60 to 70 percent reduction in emissions.

I worry that effective corrective measures will not be instituted soon enough. Climate does not necessarily change gradually. The multiple factors that are now destabilizing the global climate system could cause it to jump abruptly out of its current state. At any time, the world could suddenly become much hotter or even much colder. Such a sudden, catastrophic change is the ultimate health risk—one that must be avoided at all costs. SA

The Author

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Form from Fire

Self-propagating heat waves can engender new and improved materials, but only recently have researchers found ways to monitor these ultraquick chemical reactions

by Arvind Varma

Think of a burning trail of gunpowder. The fire races along its length, leaving nothing behind except loose ash and gases. Now imagine igniting the end of a different trail of powder. This time the bright, glowing wave of heat that surges through the mixture leaves a solidified mass in its wake. This seemingly paradoxical effect—that burning need not always use up materials or break them down—is entirely real and is the essence of one of the most promising innovations in materials science: combustion synthesis.

Scientists have known about combustion synthesis for three decades, and they have learned to create more than 500 compounds, many of which have proved to be invaluable as ball bearings, nuclear safety shields, abrasives, high-temperature superconductors and other technologically advanced items [*see box on page 61*]. But despite this long history, trial and error has been the primary means of invention. For example, a researcher might eventually realize that starting with finer powders can make the synthesized material stronger, but he or she could only guess at the reasons why. As a result, the applications of combustion synthesis have remained highly specialized. Only recently have engineers begun to understand how a heat wave actually propagates through the original mixture, leaving the desired material in its wake. Knowing precisely what happens between starting components and final product is the best way for researchers to refine techniques of combustion synthesis for widespread use.

Since prehistoric times human beings have been burning things for advantageous ends. About 13,000 years ago people discovered that baking a piece of malleable clay transformed it into hard ceramic. Modern technologists have learned how to fire special clay powders in a furnace to produce ceramic shields that are strong and heat-resistant enough to protect spacecraft. In both cases, the process applies external heat to break the chemical bonds of the original material and to rearrange them into a new structure.

When scientists observed in the late 19th century that shuffling chemical bonds can release significant heat energy, they began to wonder whether it might be possible to use this energy directly to synthesize useful materials. In 1972 scientists in the former Soviet Union discovered how to harness enough of this energy to drive a synthesis reaction without continuing to heat the mixture. Thus, combustion synthesis not only makes a new solid from disparate starting components, it also self-propagates—once heat is applied to start the reaction, it runs on its own. And all it takes to ignite a combustion-synthesis reaction is a brief heat pulse from sources such as a tungsten coil or a laser beam, which use significantly less energy than do industrial furnaces, the most common method for creating advanced materials.

Saving energy is just one of many advantages that combustion synthesis holds over conventional techniques of materials production. The energy-consuming nature and size of furnaces limit the volume of material that can be converted. Combustion synthesis can yield objects of virtually any size,

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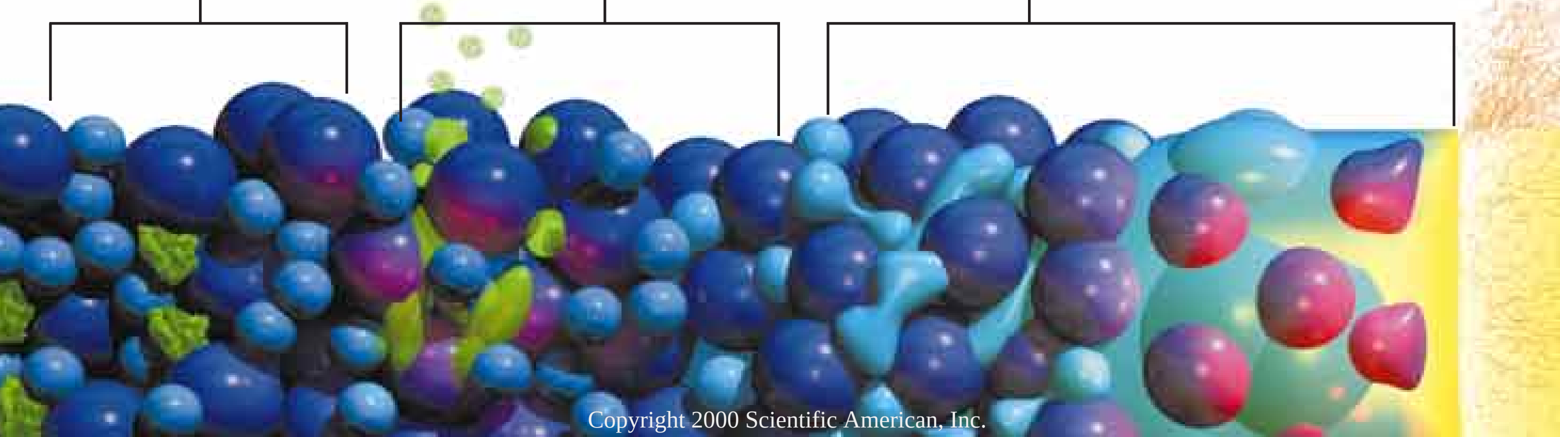


INITIAL MIXTURE HEATS UP
Contact between particles of two starting powders (*big and small spheres*) is too limited for a chemical reaction to occur at low temperatures.

IMPURITIES ESCAPE
Heating expels impurities such as water (*green*), which boils off as the temperature of the initial mixture exceeds 100 degrees Celsius.

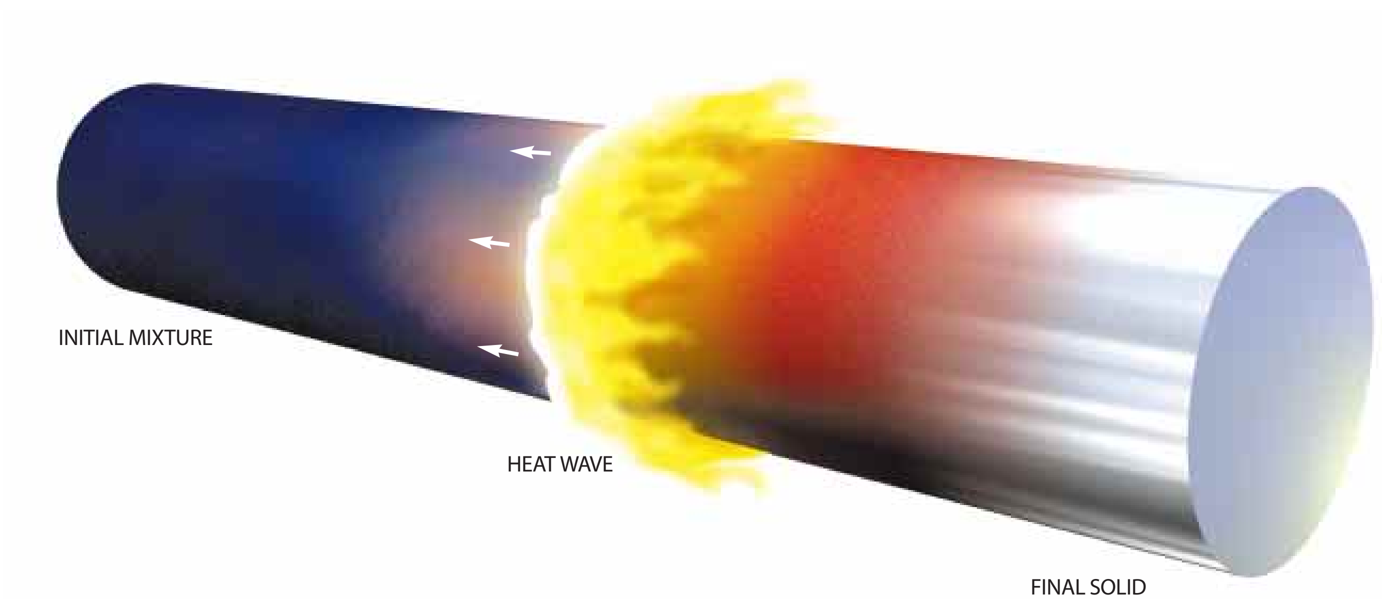
FIRST REACTANT MELTS AND SPREADS
Powder with the lower melting point (*blue*) coats other particles. Increased contact between the two reactants and higher temperatures ignite the chemical reaction.

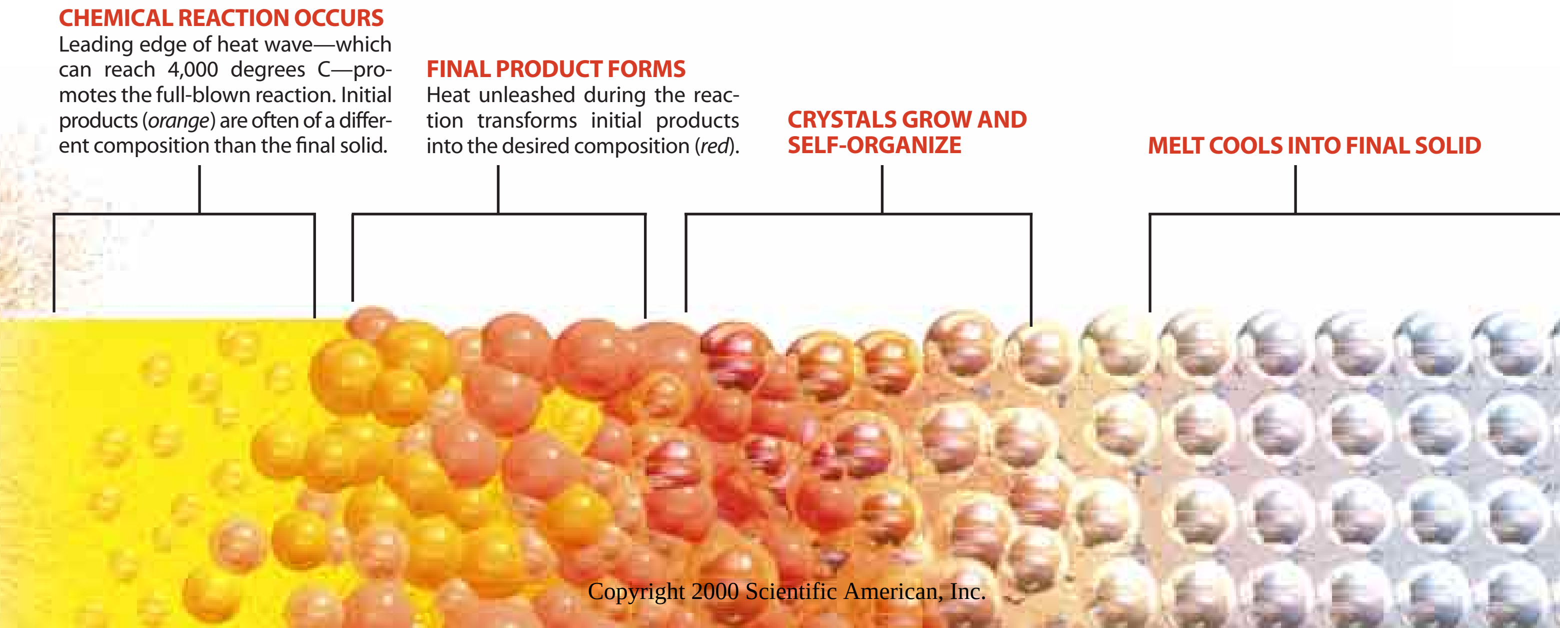
because the heat from the chemical reaction originates at every point inside the original sample. These reactions also attain temperatures anywhere from 1,500 to 4,000 degrees Celsius, and the material heats at astounding rates of up to one million degrees C per second. That means combustion synthesis takes just a few seconds to turn a mixture of reactants into a new solid, as opposed to the minutes or even hours that furnaces, which rarely reach 2,000 degrees C, require to do the same job. Intense and quick heating creates compounds with extremely uniform microscopic structures. In contrast, conventional furnaces heat material unevenly and can introduce flaws in the material's structure—a potentially fatal problem for an object that will experience tremendous stress. A microscopic crack in the metallic skin of an airplane, for example, can sometimes grow large enough to break catastrophically [see "Why Things Break," by Mark E. Eberhart; SCIENTIFIC AMERICAN, October 1999].

Combustion-synthesis reactions can involve gases, but in the most common method, called solid flame, all starting components and resulting products remain in a solid or liquid state. This type of reaction can combine metals such as nickel and aluminum to produce the lightweight and heat-resistant compounds needed for aircraft turbines and other engine parts. Starting powders are pressed into a pellet, typically in the shape of a cylinder. For some purposes, the entire pellet is heated uniformly until the reaction occurs simultaneously throughout the sample. In most cases, however, the sample is ignited only at one location, and the heat wave passes through from one end to the other.

Combustion synthesis is more than a quick and energy-efficient way to make valuable materials. The high temperatures and short reaction times can convert a compound rapidly enough to "fool" its molecules into solidifying as structures that would be unstable under normal conditions. This capability makes it possible to invent materials that are otherwise impossible to make, such as ceramics peppered with synthetic diamonds—an ideal combination for high-quality cutting tools. In slow-heating furnaces, diamond turns to soft graphite, but during rapid combustion, diamond particles retain their shape and hardness. Combustion synthesis can also yield so-called functionally graded materials, in which compounds and properties are distributed as desired. The materi-

HEAT WAVE surges back along a 10-centimeter-long rod of compressed powders (*below*) in only a few seconds. Researchers have now pinpointed exactly how the heat wave ignites chemical reactions and transforms the molecular structure to leave a new solid in its wake (*enlargement at bottom*).





al's microscopic structure may have a smooth transition, for instance, from a strong metal on one end to a heat-resistant ceramic on the other. With a gradual variation in composition, rather than abrupt boundaries between different compounds, graded materials can better resist dramatic changes in temperature and mechanical stress.

Taking a Closer—and Quicker—Look

Although combustion synthesis offers a number of potential advantages over conventional techniques, scientists must overcome some hurdles before it can enjoy widespread use. Customizing materials requires a detailed mechanistic understanding of how the new molecular structure forms—and that means being able to track what happens during each phase of the reaction. The most attractive features of combustion synthesis—high heating rates, high temperatures and short reaction times—also make it difficult to study the reaction wave as it propagates through the mixture. In response to this challenge, a new field of fundamental research is emerging.

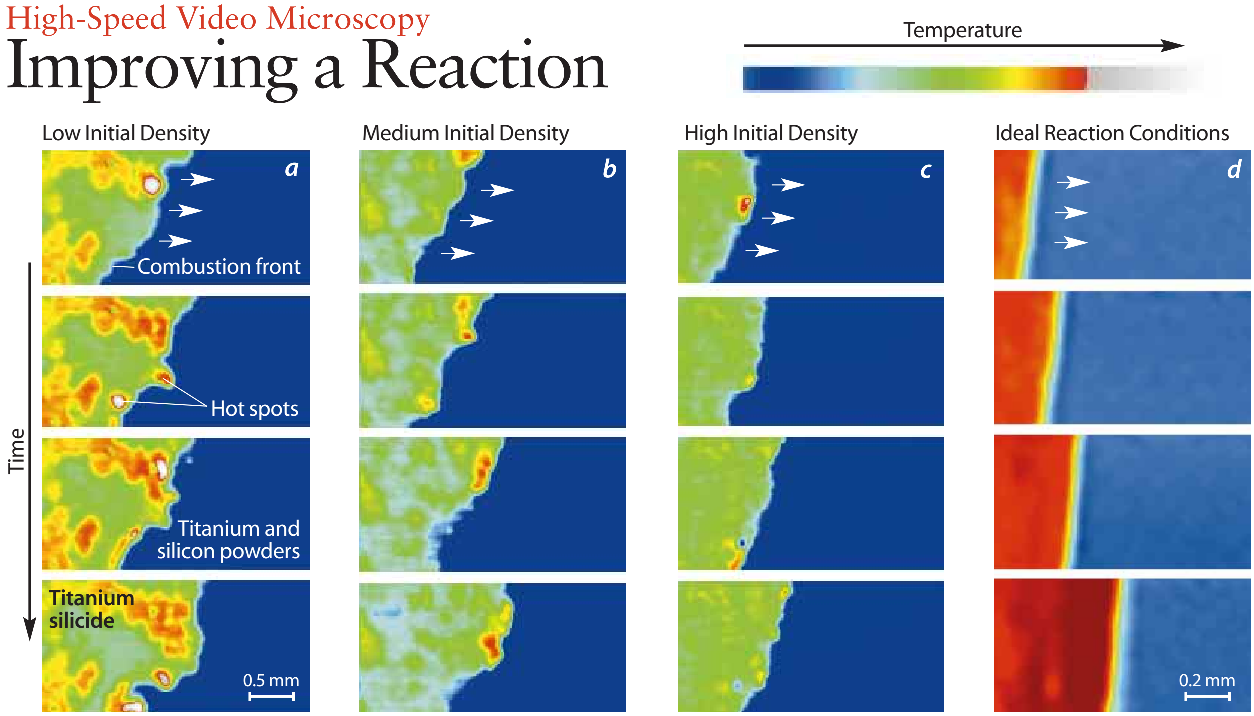
Engineers are beginning to incorporate ideas from various areas of science and engineering into their investigations of combustion reactions. From biologists who study fast muscle movement, engineers borrowed a technology with which they can monitor precisely when certain components melt and new crystals form during a reaction. In this method, called time-resolved x-ray diffraction, a machine scans the reacting sample with powerful synchrotron radiation to generate x-ray patterns of the material every 0.01 second. From these patterns, researchers can identify the composition of chemical phases that appear at a particular moment during the reaction. To identify the evolution of the microstructure, engineers employ a technique first developed to study the way solid rocket fuel burns. By dropping a burning sample into a pool of liquid argon, researchers can freeze the reaction before all the starting components have been transformed into the final product. They then slice this quenched sample into thin layers and analyze its microstructure using techniques such as electron microscopy.

As engineers began looking at combustion reactions with these new methods, they discovered that the characteristics of the material change as the reaction wave moves through different zones. Many researchers now concentrate their efforts on understanding phenomena near the leading edge of the reaction wave—also called the combustion front—because the primary compounds that define the structure and properties of the final material form there. The width of this zone generally varies from 0.05 to 0.5 millimeter, enough to hold only a few to tens of particles. Within this tiny area, several physical and chemical processes work in concert to transform the molecular structure, so researchers needed a way to monitor this specific location.

During the past six years, my colleagues and I at the University of Notre Dame have designed a tool that is especially useful for observing microscopic conditions along the combustion front. We can now watch the reaction wave pass through a material with the help of a high-speed digital video camera that peers through a microscope and sees objects as

High-Speed Video Microscopy

Improving a Reaction



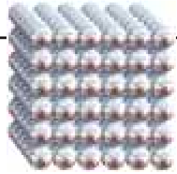
SCINTILLATING WAVE characterizes many combustion-synthesis reactions, including the formation of titanium silicide. Four high-speed video frames show that silicon melts and surrounds solid particles of titanium, initiating a reaction (*red*). The heat wave moves forward only as these "hot spots" appear (*a*). This highly variable temperature at the leading edge of the reaction, also called the combustion front, is a problem because it causes nonuniformity in the microstructure of the final product. Starting a reaction in samples of higher density, which can more efficiently dissipate heat, decreases the occurrence of hot spots (*b* and *c*) and results in a more uniform microstructure. Researchers strive for reaction conditions that yield a quasi-homogeneous wave, which moves steadily and shows relatively little variation of temperature along the combustion front (*d*).

ARVIND VARMA AND ALEXANDER S. MUKASYAN *University of Notre Dame* small as 0.0015 millimeter in diameter ($^{1}/_{50}$ the thickness of human hair). Our camera captures up to 12,000 frames per second; a conventional video camera captures only 30 frames per second. Using this technique, we have discovered that a reaction that appears to travel steadily on visible scales may move in a complex, unsteady fashion on the microscopic level.

Given this new information about the microstructure of the transforming material, we classified the reaction waves into two general types: quasi-homogeneous and scintillating. A quasi-homogeneous wave moves steadily, and the temperature varies relatively little along the combustion front. Such conditions are ideal for making a material with a highly uniform structure. The combustion front of a scintillating wave, in contrast, displays extreme temperature variation, which may lead to flaws in the final solid. This wave pattern occurs in systems in which at least one reactant melts during the reaction. Particles of the reactant with the lower melting point begin to melt just ahead of the combustion front, and the reaction wave moves forward only as these "hot spots" appear.

Characterizing waves in such detail has become possible only in the past two years, but what my colleagues and I find most exciting is that knowing these details allows us to precisely tailor properties of the final compound. In reactions that travel as scintillating waves, we can control the appearance of hot spots by carefully selecting the experimental conditions. Reactions between titanium and silicon, for example, produce fewer hot spots—and therefore less temperature variation along the combustion front—when we increase the density of the pellet of starting powders [*see illustration on opposite page*].

New ways of analyzing combustion reactions have opened the door for scientists to invent new materials more efficiently. One such example is the enhancement of cobalt-based alloys, widely used in orthopedic implants such as artificial hips and knees. For decades, the technology for making implants has involved melting ingots of the alloys in furnaces and pouring them into molds of the proper shape. My colleagues and I are working both to make stronger alloys and to eliminate manufacturing steps by synthesizing the implant directly within its mold. Developing this one-step technology—and other applications of combustion synthesis—will take several years, but high-speed video microscopy and other methods for tracking these ultraquick reactions may bring combustion synthesis to the forefront of materials production technology. SA



Combustion Synthesis

What It's Good For

COMPOSITION	APPLICATIONS
CARBIDES Carbon plus an element such as titanium or silicon (TiC, SiC)	Abrasives, cutting tools, ceramic reinforcements
BORIDES Boron plus a metal such as titanium or lanthanum (TiB_2, LaB_6)	Abrasives, cutting tools, cathodes
SILICIDES Silicon plus a metal such as titanium or molybdenum ($TiSi_2$, $MoSi_2$)	Heating elements, electrical connectors, Schottky barriers for electronics
ALUMINIDES AND TITANITES Aluminum or titanium plus a metal such as nickel ($AlNi$, $TiNi$)	Aerospace and turbine materials, shape-memory alloys
NITRIDES Nitrogen plus an element such as niobium or silicon (NbN, Si_3N_4)	Ceramic engine parts, ball bearings, nuclear safety shields
HYDRIDES Hydrogen plus one or more metals (MgH_2, $ZrNiH_3$)	Hydrogen storage, catalytic materials
OXIDES Oxygen plus one or more metals ($YBa_2Cu_3O_{7-x}$, $La_{0.8}Sr_{0.2}CrO_3$)	High-temperature superconductors, gas sensors, fuel cells
CHALCOGENIDES AND PHOSPHIDES Sulfur or phosphorus plus a metal such as molybdenum or gallium	High-temperature lubricants, semiconductors

The Author

ARVIND VARMA has been investigating the combustion synthesis of advanced materials in his laboratory at the University of Notre Dame for the past 10 years. His interest in other areas of chemical engineering began at the University of Minnesota, where he received his Ph.D. in 1972. He worked for two years at Union Carbide before joining the Notre Dame faculty in 1975. There he has served as Arthur J. Schmitt Professor since 1988.

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The Universe's UNSEEN DIMENSIONS

The visible universe could lie on a membrane floating within a higher-dimensional space. The extra dimensions would help unify the forces of nature and could contain parallel universes

by Nima Arkani-Hamed, Savas Dimopoulos and Georgi Dvali

The classic 1884 story *Flatland: A Romance of Many Dimensions,* by Edwin A. Abbott, describes the adventures of "A. Square," a character who lives in a two-dimensional world populated by animated geometric figures—triangles, squares, pentagons, and so on. Toward the end of the story, on the first day of 2000, a spherical creature from three-dimensional "Spaceland" passes through Flatland and carries A. Square up off his planar domain to show him the true three-dimensional nature of the larger world. As he comes to grasp what the sphere is showing him, A. Square speculates that Spaceland may itself exist as a small subspace of a still larger four-dimensional universe.

Amazingly, in the past two years physicists have begun seriously examining a very similar idea: that everything we can see in our universe is confined to a three-dimensional "membrane" that lies within a higher-dimensional realm. But unlike A. Square, who had to rely on divine intervention from Spaceland for his insights, physicists may soon be able to detect and verify the existence of reality's extra dimensions, which could extend over distances as large as a millimeter ($1/25$ of an inch). Experiments are already looking for the extra dimensions' effect on the force of gravity. If the theory is correct, upcoming high-energy particle experiments in Europe could see unusual processes involving quantum gravity, such as the creation of transitory micro black holes. More than just an idle romance of many dimensions, the theory is based on some of the most recent developments in string theory and would solve some long-standing puzzles of particle physics and cosmology.

The exotic concepts of string theory and multidimensions actually arise from attempts to understand the most familiar of forces: gravity. More than three centuries after Isaac Newton proposed his law of gravitation, physics still does not explain why gravity is so much weaker than all the other forces. The feebleness of gravity is dramatic. A small magnet readily overcomes the gravitational pull of the entire mass of the earth when it lifts a nail off the ground. The gravitational attraction between two electrons is 10^{43} times weaker than the repulsive electric force between them. Gravity seems important to us—keeping our feet on the ground and the earth orbiting the sun—only because these large aggregates of matter are electrically neutral, making the electrical forces vanishingly small and leaving gravity, weak as it is, as the only noticeable force left over.

The Inexplicable Weakness of Gravity

Electrons would have to be 10^{22} times more massive for the electric and gravitational forces between two of them to be equal. To produce such a heavy particle would take 10^{19} gigaelectron volts (GeV) of energy, a quantity known as the Planck energy. A related quantity is the Planck length, a tiny 10^{-35} meter. By comparison, the nucleus of a hydrogen atom, a proton, is about 10^{19} times as large and has a mass of about 1 GeV. The Planck scale of energy and length is far out of reach of the most powerful accelerators. Even the Large Hadron Collider at CERN will probe distances only down to about 10^{-19} meter when it commences operations five years from now [see "The Large Hadron Collider," by Chris Llewellyn Smith; SCIENTIFIC AMERICAN, July]. Because gravity becomes comparable in strength to electromagnetism and the other forces at the Planck scale, physicists have traditionally assumed that the theory unifying gravity with the other interactions would reveal itself only at these energies. The nature of the ultimate unified theory would then be hopelessly out of reach of direct experimental

MEMBRANE UNIVERSE in a higher-dimensional realm could be where we live. Experiments might detect signs of extra dimensions as "large" as a millimeter this year.

BRYAN CHRISTIE

investigation in the foreseeable future [see "A Unified Physics by 2050?" by Steven Weinberg; SCIENTIFIC AMERICAN, December 1999].

Today's most powerful accelerators probe the energy realm between 100 and 1,000 GeV (one teraelectron volt, or TeV). In this range, experimenters have seen the electromagnetic force and the weak interaction (a force between subatomic particles responsible for certain types of radioactive decay) become unified. We would understand gravity's extraordinary weakness if we understood the factor of 10^{16} that separates the electroweak scale from the Planck scale.

Alas, physicists' extremely successful theory of particle physics, called the Standard Model, cannot explain the size of this huge gap, because the theory is carefully adjusted to fit the observed electroweak scale. The good news is that this adjustment (along with about 16 others) serves once and for all to fit myriad observations. The bad news is that we must fine-tune the underlying theory to an accuracy of about one part in 10^{32}; otherwise, quantum effects—instabilities—would drag the electroweak scale all the way back up to the Planck scale. The presence of such delicate balancing in the theory is like walking into a room and finding a pencil standing perfectly on its tip in the middle of a table. Though not impossible, the situation is highly unstable, and we are left wondering how it came about.

For 20 years, theorists have attacked this conundrum, called the hierarchy problem, by altering the nature of particle physics near 10^{-19} meter (or 1 TeV) to stabilize the electroweak scale. The most popular modification of the Standard Model that achieves this goal involves a new symmetry called supersymmetry. Going back to our pencil analogy, supersymmetry acts like an invisible thread holding up the pencil and preventing it from falling over. Although accelerators have not yet turned up any direct evidence for supersymmetry, some suggestive indirect evidence supports the supersymmetric extension of the Standard Model. For example, when the measured strengths of the strong, weak and electromagnetic forces are theoretically extrapolated to shorter distances, they meet very accurately at a common value only if supersymmetric rules govern the extrapolation. This result hints at a supersymmetric unification of these three forces at about 10^{-32} meter, about 1,000 times larger than the Planck length but still far beyond the range of particle colliders.

Gravity and Large Spatial Dimensions

For two decades, the only viable framework for tackling the hierarchy problem has been to change particle physics near 10^{-19} meter by introducing new processes such as supersymmetry. But in the past two years theorists have proposed a radically different approach, modifying space-time, gravity and the Planck scale itself. The key insight is that the extraordinary size of the Planck scale, accepted for a century since Planck first introduced it, is based on an untested assumption about how gravity behaves over short distances.

Newton's inverse square law of gravity—which says the force between two masses falls as the square of the distance between them—works extremely well over macroscopic distances, explaining the earth's orbit around the sun, the moon's around the earth, and so on. But because gravity is so weak, the law has been experimentally tested down to distances of only about a millimeter, and we must extrapolate across 32 orders of magnitude to conclude that gravity only becomes strong at a Planck scale of 10^{-35} meter.

The inverse square law is natural in three-dimensional space [*see upper illustration on opposite page*]. Consider lines of gravitational force emanating uniformly from the earth. Farther from the earth, the lines are spread over a spherical shell of greater area. The surface area increases as the square of the distance, and so the force is diluted at that rate. Suppose there were one more dimension, making space four-dimensional. Then the field lines emanating from a point would get spread over a four-dimensional shell whose surface would increase as the cube of the distance, and gravity would follow an inverse cube law.

The inverse cube law certainly doesn't describe our universe, but now imagine that the extra dimension is curled up into a small circle of radius R and that we're looking at field lines coming from a tiny point mass [*see lower illustration on opposite page*]. When the field lines are much closer to the mass than the distance R, they can spread uniformly in all four dimensions, and so the force of gravity falls as the inverse cube of distance. Once the lines have spread fully around the circle, however, only three dimensions remain for them to continue spreading through, and so for distances much greater than R the force varies as the inverse square of the distance.

The same effect occurs if there are many extra dimensions, all curled up into circles of radius R. For n extra spatial dimensions at distances smaller than R, the force of gravity will follow an inverse $2 + n$ power law. Because we have measured gravity only down to a millimeter, we would be oblivious to changes in gravity caused by extra dimensions whose size R is smaller than a millimeter. Furthermore, the $2 + n$ power law would cause gravity to reach "Planck-scale strength" well above 10^{-35} meter. That is, the Planck length (defined by where gravity becomes strong) would not be that small, and the hierarchy problem would be reduced.

One can solve the hierarchy problem completely by postulating enough extra dimensions to move the Planck scale very

IN A NUTSHELL

Dimensions. Our universe seems to have four dimensions: three of space (up-down, left-right, forward-backward) and one of time. Although we can barely imagine additional dimensions, mathematicians and physicists have long analyzed the properties of theoretical spaces that have any number of dimensions.

Size of dimensions. The four known space-time dimensions of our universe are vast. The dimension of time extends back at least 13 billion years into the past and may extend infinitely into the future. The three spatial dimensions may be infinite; our telescopes have detected objects more than 12 billion light-years away. Dimensions can also be finite. For example, the two dimensions of the surface of the earth extend only about 40,000 kilometers—the length of a great circle.

Small extra dimensions. Some modern physics theories postulate additional real dimensions that are wrapped up in circles so small (perhaps 10^{-35}-meter radius) that we have not detected them. Think of a thread of cotton: to a good approximation, it is one-dimensional. A single number can specify where an ant stands on the thread. But using a microscope, we see dust mites crawling on the thread's two-dimensional surface: along the large length dimension and around the short circumference dimension.

Large extra dimensions. Recently physicists realized that extra dimensions as "big" as a millimeter could exist and remain invisible to us. Surprisingly, no known experimental data rule out the theory, and it could explain several mysteries of particle physics and cosmology. We and all the contents of our known three-dimensional universe (except for gravity) would be stuck on a "membrane," like pool balls moving on the two-dimensional green baize of a pool table.

Dimensions and gravity. The behavior of gravity—particularly its strength—is intimately related to how many dimensions it pervades. Studies of gravity acting over distances smaller than a millimeter could thus reveal large extra dimensions to us. Such experiments are under way. These dimensions would also enhance the production of bizarre quantum gravity objects such as micro black holes, graviton particles and superstrings, all of which could be detected sometime this decade at high-energy particle accelerators.

—Graham P. Collins, staff writer

BALLS ON A POOL TABLE are analogous to fundamental particles on the membrane that is our known universe. Billiard-ball collisions radiate energy into three dimensions as sound waves (*red*), analogous to gravitons. Precise studies of the balls' motions could detect the "missing" energy and thus the higher dimensions.

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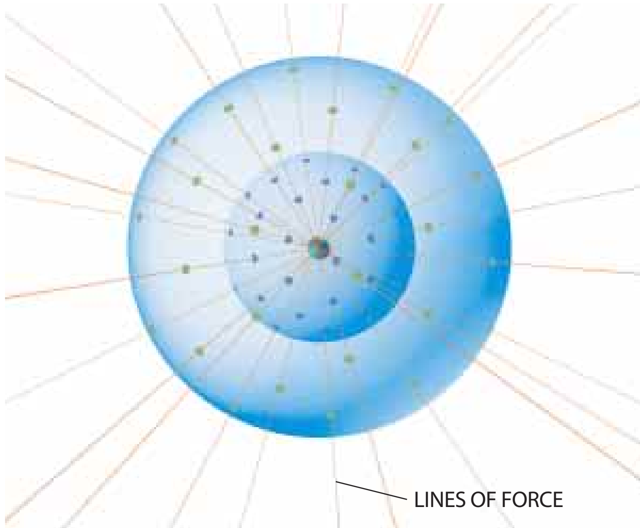
close to the electroweak scale. The ultimate unification of gravity with the other forces would then take place near 10^{-19} meter rather than 10^{-35} meter as traditionally assumed. How many dimensions are needed depends on how large they are. Conversely, for a given number of extra dimensions we can compute how large they must be to make gravity strong near 10^{-19} meter. If there is only one extra dimension, its radius R must be roughly the distance between the earth and the sun. Therefore, this case is already excluded by observation. Two extra dimensions, however, can solve the hierarchy problem if they are about a millimeter in size—precisely where our direct knowledge of gravity ends. The dimensions are smaller still if we add more of them, and for seven extra dimensions we need them to be around 10^{-14} meter big, about the size of a uranium nucleus. This is tiny by everyday standards but huge by the yardstick of particle physics.

Postulating extra dimensions may seem bizarre and ad hoc, but to physicists it is an old, familiar idea that dates back to the 1920s, when Polish mathematician Theodor Kaluza and Swedish physicist Oskar Klein developed a remarkable unified theory of gravity and electromagnetism that required one extra dimension. The idea has been revived in modern string theories, which require a total of 10 spatial dimensions for internal mathematical consistency. In the past, physicists have assumed that the extra dimensions are curled up into tiny circles with a size near the traditional Planck length of 10^{-35} meter, making them undetectable but also leaving the conundrum of the hierarchy problem. In contrast, in the new theory that we are discussing, the extra dimensions are wrapped into big circles of at least 10^{-14} meter radius and perhaps as enormous as a millimeter.



GRAVITATIONAL LINES OF FORCE spread out from the earth in three dimensions. As distance from the earth increases, the force becomes diluted by being spread across a larger surface area (*spheres*). The surface area of each sphere increases as the square of its radius, so gravity falls as the inverse square of distance in three dimensions.

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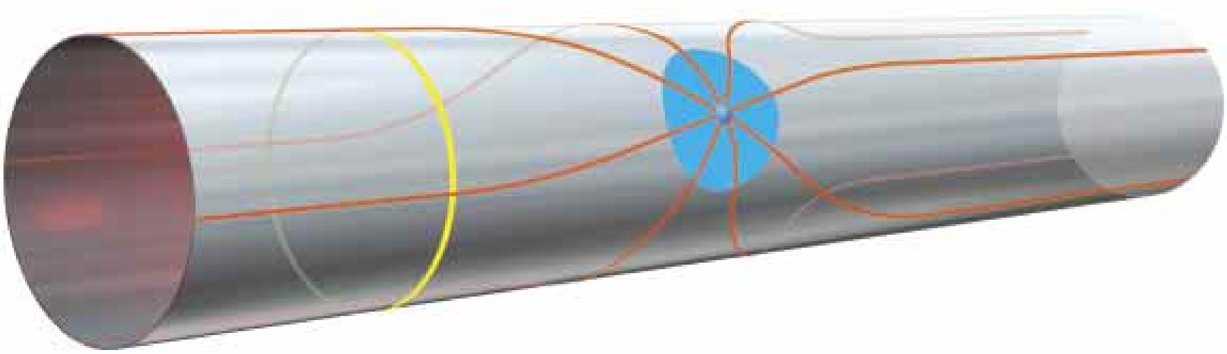
Our Universe on a Wall

If these dimensions are that large, why haven't we seen them yet? Extra dimensions a millimeter big would be discernible to the naked eye and obvious through a microscope. And although we have not measured gravity below about a millimeter, we have a wealth of experimental knowledge concerning all the other forces at far shorter distances approaching 10^{-19} meter, all of it consistent only with three-dimensional space. How could there possibly be large extra dimensions?

The answer is at once simple and peculiar: all the matter and forces we know of—with the sole exception of gravity—are stuck to a "wall" in the space of the extra dimensions [*see illustration on next page*]. Electrons and protons and photons and all the other particles in the Standard Model cannot move in the extra dimensions; electric and magnetic field lines cannot spread into the higher-dimensional space. The wall has only three dimensions, and as far as these particles are concerned, the universe might as well be three-dimensional. Only gravitational field lines can extend into the higher-dimensional space, and only the particle that transmits gravity, the graviton, can travel freely into the extra dimensions. The presence of the extra dimensions can be felt only through gravity.

To make an analogy, imagine that all the particles in the Standard Model, like electrons and protons, are billiard balls moving on the surface of a vast pool table. As far as they are concerned, the universe is two-dimensional. Nevertheless, pool-table inhabitants made out of "billiard balls" could still detect the higher-dimensional world: when two balls hit each other sufficiently hard, they produce sound waves, which travel in all three dimensions, carrying some energy away from the table surface [*see illustration on opposite page*]. The sound waves are analogous to gravitons, which can travel in



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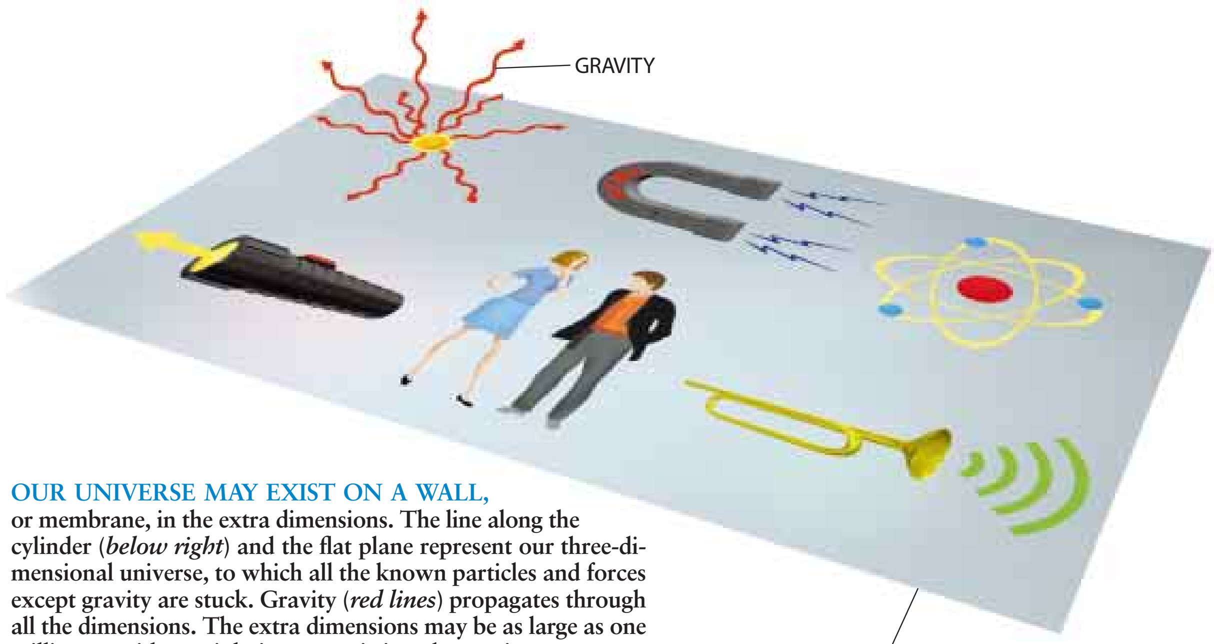
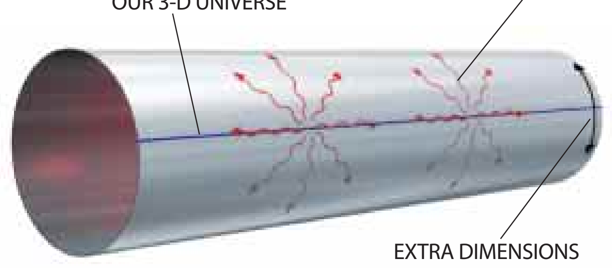
SMALL EXTRA DIMENSION wrapped in a circle (*circumference of tube*) modifies how gravity (*red lines*) spreads in space. At distances smaller than the circle radius (*blue patches*), the lines of force spread apart rapidly through all the dimensions. At much larger distances (*yellow circle*), the lines have filled the extra dimension, and it has no further effect on them.





OUR UNIVERSE MAY EXIST ON A WALL, or membrane, in the extra dimensions. The line along the cylinder (*below right*) and the flat plane represent our three-dimensional universe, to which all the known particles and forces except gravity are stuck. Gravity (*red lines*) propagates through all the dimensions. The extra dimensions may be as large as one millimeter without violating any existing observations.

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the full higher-dimensional space. In high-energy particle collisions, we expect to observe missing energy, the result of gravitons escaping into the extra dimensions.

Although it may seem strange that some particles should be confined to a wall, similar phenomena are quite familiar. For instance, electrons in a copper wire can move only along the one-dimensional space of the wire and do not travel into the surrounding three-dimensional space. Likewise, water waves travel primarily on the surface of the ocean, not throughout its depth. The specific scenario we are describing, in which all particles except gravity are stuck to a wall, can arise naturally in string theory. In fact, one of the major insights triggering recent breakthroughs in string theory has been the recognition that the theory contains such "walls," known as D-branes, where "brane" comes from the word "membrane" and "D" stands for "Dirichlet," which indicates a mathematical property of the branes. D-branes have precisely the required features: particles such as electrons and photons are represented by tiny lengths of string that each have two endpoints that must be stuck to a D-brane. Gravitons, on the other hand, are tiny closed loops of string that can wander into all the dimensions because they have no endpoints anchoring them to a D-brane.

Is It Alive?

One of the first things good theorists do when they have a new theory is to try to kill it by finding an inconsistency with known experimental results. The theory of large extra dimensions changes gravity at macroscopic distances and alters other physics at high energies, so surely it is easy to kill. Remarkably, however, despite its radical departure from our usual picture of the universe, this theory does not contradict any known experimental results. A few examples of the sorts of tests that are passed shows how surprising this conclusion is.

One might initially worry that changing gravity would affect objects held together by gravity, such as stars and galaxies. But they are not affected. Gravity changes only at distances shorter than a millimeter, whereas in a star, for example, gravity acts across thousands of kilometers to hold distant parts of the star together. More generally, even though the extra dimensions strengthen gravity much more quickly than usual at short distances, it still only catches up with the other forces near 10^{-19} meter and remains very feeble compared with them at larger distances.

A much more serious concern relates to gravitons, the hypothetical particles that transmit gravity in a quantum theory. In the theory with extra dimensions, gravitons interact much more strongly with matter (which is equivalent to gravity being stronger at short distances), so many more of them should be produced in high-energy particle collisions. In addition, they propagate in all the dimensions, thus taking energy away from the wall, or membrane, that is the universe where we live.

When a star collapses and then explodes as a supernova, the high temperatures can readily boil off gravitons into extra dimensions [*see upper illustration on page 68*]. From observations of the famous Supernova 1987A, however, we know that a supernova explosion emits most of its energy as neutrinos, leaving little room for any energy leakage by gravitons. Our understanding of supernovae therefore limits how strongly gravitons can couple to matter. This constraint could easily have killed the idea of large extra dimensions, but detailed calculations show that the theory survives. The most severe limit is for only two extra dimensions, in which case gravitons cool supernovae too much if the fundamental Planck scale is reduced below about 50 TeV. For three or more extra dimensions, this scale can be as low as a few TeV without causing supernovae to fizzle.

Theorists have examined many other possible constraints based on unacceptable changes in systems ranging from the successful big bang picture of the early universe to collisions of ultrahigh-energy cosmic rays. The theory passes all these experimental checks, which turn out to be less stringent than the supernova constraint. Perhaps surprisingly, the constraints become less severe as more dimensions are added to the theory. We saw this right from the start: the case of one extra dimension was excluded immediately because gravity would be altered at solar system distances. This indicates why more dimensions are safer; the dramatic strengthening of gravity begins at shorter distances and therefore has a smaller impact on the larger-distance processes.

Answers by 2010

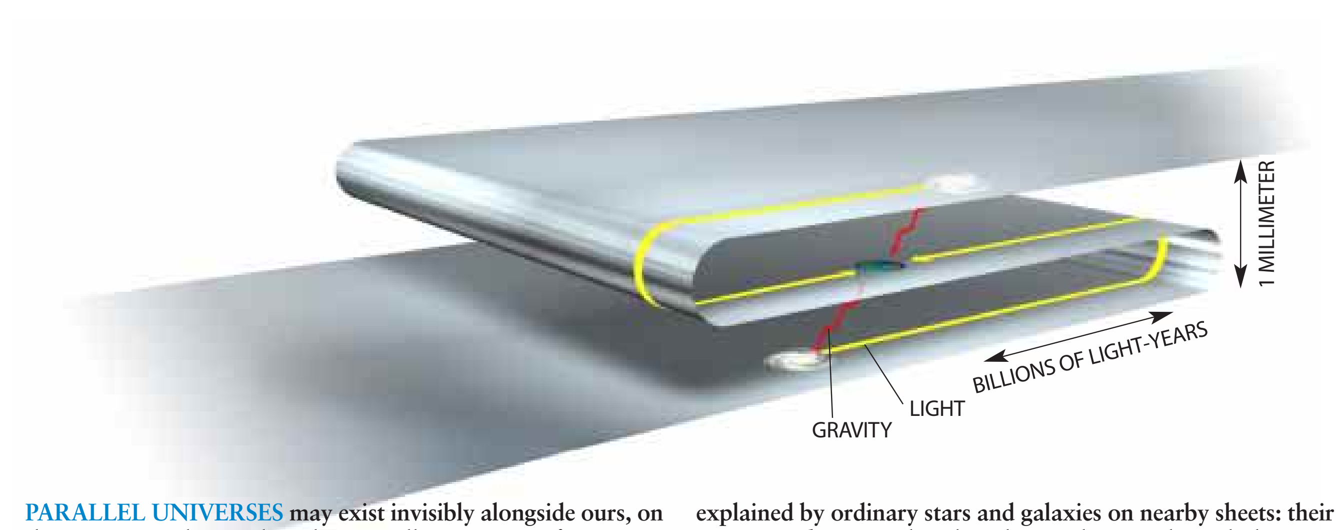
The theory solves the hierarchy problem by making gravity a strong force near TeV energies, precisely the energy scale to be probed using upcoming particle accelerators. Experiments at the Large Hadron Collider (LHC), due to begin around 2005, should therefore uncover the nature of quantum gravity! For instance, if string theory is the correct description of quantum gravity, particles are like tiny loops of string, which can vibrate like a violin string. The known fundamental particles correspond to a string that is not vibrating, much like an unbowed violin string. Each different "musical note" that a string can carry by vibrating would appear as a different exotic new particle. In conventional string theories, the strings have been thought of as only 10^{-35} meter big, and the new particles would have masses on the order of the traditional Planck energy—the "music" of such strings would be too high-pitched for us to "hear" at particle colliders. But with large extra dimensions, the strings are much longer, near 10^{-19} meter, and the new particles would appear at TeV energies—low enough to hear at the LHC.

Similarly, the energies needed to create micro black holes in particle collisions would fall within experimental range [*see lower illustration on next page*]. Such holes, about 10^{-19} meter in size, would be too small to cause problems—they would emit energy called Hawking radiation and evaporate in less than 10^{-27} second. By observing such phenomena, physicists could directly probe the mysteries of quantum black hole physics.

Even at energies too low to produce vibrating strings or black holes, particle collisions will produce large numbers of gravitons, a process that is negligible in conventional theories. The experiments could not directly detect the emitted gravitons, but the energy they carry off would show up as energy missing from the collision debris. The theory predicts specific properties of the missing energy—how it should vary with collision energy and so on—so evidence of graviton production can be distinguished from other processes that can carry off energy in unseen particles. Current data from the highest-energy accelerators already mildly constrain the large-dimensions scenario. Experiments at the LHC should either see evidence of gravitons or begin to exclude the theory by their absence.

A completely different type of experiment could also substantiate the theory, perhaps much sooner than the particle colliders. Recall that for two extra dimensions to solve the hierarchy problem, they must be as large as a millimeter. Measurements of gravity would then detect a change from Newton's inverse square law to an inverse fourth power law at distances near a millimeter. Extensions of the basic theoretical framework lead to a whole host of other possible deviations from Newtonian gravity, the most interesting of which is *repulsive* forces more than a million times stronger than gravity occurring between masses separated by less than a millimeter. Tabletop experiments using exquisitely built detectors are now under way, testing Newton's law from the centimeter range down to tens of microns [*see illustration on page 69*].

To probe the gravitational force at submillimeter distances, one must use objects not much larger than a millimeter, which therefore have very small masses. One must carefully screen out numerous effects such as residual electrostatic forces that could mask or fake the tiny gravitational attraction. Such experiments are difficult and subtle, but it is exciting that they might uncover dramatic new physics. Even apart from the search for extra dimensions, it is important to extend our direct knowledge of gravity to these short distances. Three researchers are currently conducting such experiments: John C. Price of the University of Colorado, Aharon Kapitulnik of Stanford University and Eric G. Adel-



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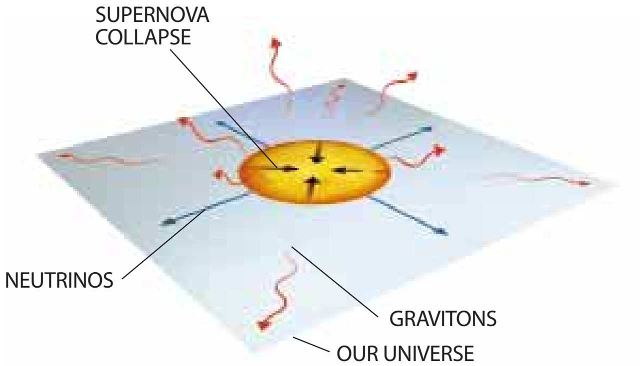
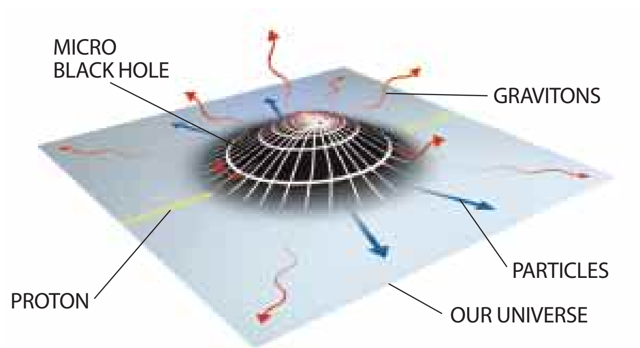
PARALLEL UNIVERSES may exist invisibly alongside ours, on their own membranes less than a millimeter away from ours. Such parallel universes could also be different sheets of our own universe folded back on itself. So-called dark matter could be explained by ordinary stars and galaxies on nearby sheets: their gravity (*red*) can reach us by taking a shortcut through the extra dimensions, but we cannot see them because light (*yellow*) must travel billions of light-years to the folds and back.



SUPERNOVA occurs when the collapse of a massive star produces an explosive shock wave. Most of the energy is emitted as neutrinos (*blue*). If extra dimensions exist, radiated gravitons (*red*) carry away more energy than they would in three dimensions. Theorists constrain the properties of the extra dimensions by requiring that energy leakage by gravitons not cause supernovae to fizzle.



MICRO BLACK HOLES could be created by particle accelerators such as the Large Hadron Collider smashing together protons (*yellow*) at high energies. The holes would evaporate rapidly by emitting Hawking radiation of Standard Model particles (*blue*) and gravitons (*red*).

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berger of the University of Washington. They expect preliminary results this year.

The idea of extra dimensions in effect continues the Copernican tradition in understanding our place in the world: The earth is not the center of the solar system, the sun is not the center of our galaxy, our galaxy is just one of billions in a universe that has no center, and now our entire three-dimensional universe would be just a thin membrane in the full space of dimensions. If we consider slices across the extra dimensions, our universe would occupy a single infinitesimal point in each slice, surrounded by a void.

Perhaps this is not the full story. Just as the Milky Way is not the only galaxy in the universe, might our universe not be alone in the extra dimensions? The membranes of other three-dimensional universes could lie parallel to our own, only a millimeter removed from us in the extra dimensions [*see illustration on preceding page*]. Similarly, although all the particles of the Standard Model must stick to our own membrane universe, other particles beyond the Standard Model in addition to the graviton might propagate through the extra dimensions. Far from being empty, the extra dimensions could have a multitude of interesting structures.

The effects of new particles and universes in the extra dimensions may provide answers to many outstanding mysteries of particle physics and cosmology. For example, they may account for the masses of the ghostly elementary particles called neutrinos. Impressive new evidence from the Super Kamiokande experiment in Japan indicates that neutrinos, long assumed to be massless, have a minuscule but nonzero mass [see "Detecting Neutrino Mass," by Edward Kearns, Takaaki Kajita and Yoji Totsuka; SCIENTIFIC AMERICAN, August 1999]. The neutrino can gain its mass by interacting with a partner field living in the extra dimensions. As with gravity, the interaction is greatly diluted by the partner being spread throughout the extra dimensions, and so the neutrino acquires only a tiny mass.

Parallel Universes

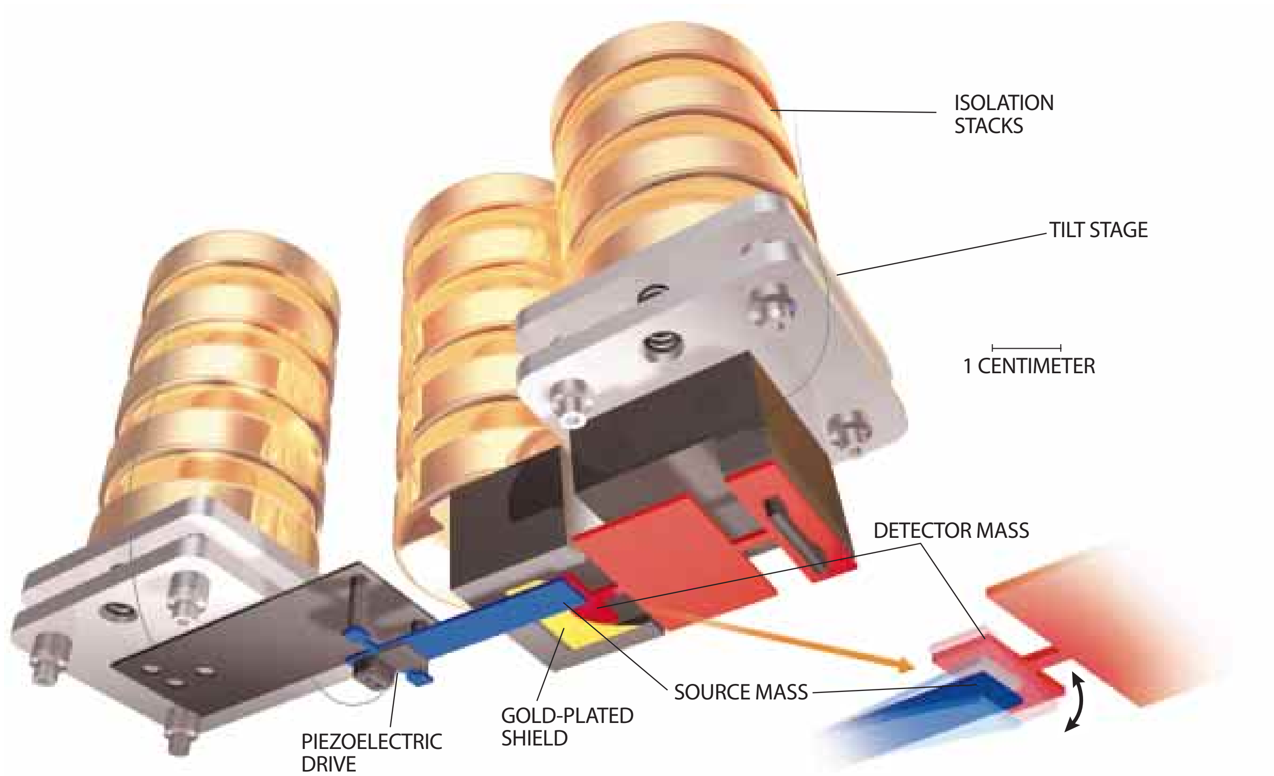
Another example is the mystery in cosmology of what constitutes "dark matter," the invisible gravitating substance that seems to make up more than 90 percent of the mass of the universe. Dark matter may reside in parallel universes. Such matter would affect our universe through gravity and is necessarily "dark" because our species of photon is stuck to our membrane, so photons cannot travel across the void from the parallel matter to our eyes.

Such parallel universes might be utterly unlike our own, having different particles and forces and perhaps even being confined to membranes with fewer or more dimensions. In one intriguing scenario, however, they have identical properties to our own world. Imagine that the wall where we live is folded a number of times in the extra dimensions [*see illustration on preceding page*]. Objects on the other side of a fold will appear to be very distant even if they are less than a millimeter from us in the extra dimensions: the light they emit must travel to the crease and back to reach us. If the crease is tens of billions of light-years away, no light from the other side could have reached us since the universe began.

Dark matter could be composed of ordinary matter, perhaps even ordinary stars and galaxies, shining brightly on their own folds. Such stars would produce interesting observable effects, such as gravitational waves from supernovae and other violent astrophysical processes. Gravity-wave detectors scheduled for completion in a few years could find evidence for folds by observing large sources of gravitational radiation that cannot be accounted for by matter visible in our own universe.

The theory we have presented here was not the first proposal involving extra dimensions larger than 10^{-35} meter. In 1990 Ignatios Antoniadis of École Polytechnique in France suggested that some of string theory's dimensions might be as large as 10^{-19} meter, but he kept the scale of quantum gravity near 10^{-35} meter. In 1996 Petr Hořava of the California Institute of Technology and Edward Witten of the Institute for Advanced Study in Princeton, N.J., pointed out that a single extra dimension of 10^{-30} meter would neatly unify gravity along with the supersymmetric unification of the other forces, all at 10^{-32} meter. Following this idea, Joseph Lykken of Fermi National Accelerator Laboratory in Batavia, Ill., attempted to lower the unification scale to near 10^{-19} meter (without invoking large extra dimensions). Keith Dienes of the University of Arizona and Emilian Dudas and Tony Gherghetta of CERN observed in 1998 that extra dimensions smaller than 10^{-19} meter could allow the forces to unify at much larger distances than 10^{-32} meter.

Since our proposal in 1998 a number of interesting varia-



TORSION OSCILLATOR at the University of Colorado looks for changes in gravity from 0.05 to 1.0 millimeter. Piezoelectrics vibrate the tungsten source mass (*blue*) like a diving board. Any forces acting between the source mass and the tungsten detector (*red*) produce twisting oscillations of the detector (*inset; oscillations are exaggerated*), which are sensed by electronics. A gold-plated shield (*yellow*) suppresses electrostatic forces, and suspension from brass isolation stacks stops vibrations from traveling from the source to the detector. Electrostatic shields enclosing the apparatus are not shown. Results at room temperature (300 kelvins) are expected this year. For maximum sensitivity, liquid helium will cool the apparatus to four kelvins.

tions have appeared, using the same basic ingredients of extra dimensions and our universe-on-a-wall. In an intriguing model, Lisa Randall of Princeton University and Raman Sundrum of Stanford proposed that gravity itself may be concentrated on a membrane in a five-dimensional space-time that is infinite in all directions. Gravity appears very weak in our universe in a natural way if we are on a different membrane.

For 20 years, the conventional approach to tackling the hierarchy problem, and therefore understanding why gravity is so weak, has been to assume that the Planck scale near 10^{-35} meter is fundamental and that particle physics must change near 10^{-19} meter. Quantum gravity would remain in the realm of theoretical speculation, hopelessly out of the reach of experiment. In the past two years we have realized that this does not have to be the case. If there are large new dimensions, in the next several years we could discover deviations from Newton's law near 6×10^{-5} meter, say, and we would detect stringy vibrations or black holes at the LHC. Quantum gravity and string theory would become testable science. Whatever happens, experiment will point the way to answering a 300-year-old question, and by 2010 we will have made decisive progress toward understanding why gravity is so weak. And we may find that we live in a strange Flatland, a membrane universe where quantum gravity is just around the corner. SA

The Authors

NIMA ARKANI-HAMED, SAVAS DIMOPOULOS and GEORGI DVALI thought up the extra-dimension theory while they were together at Stanford University in February 1998. Arkani-Hamed was born in Houston in 1972 and received a Ph.D. in physics at the University of California, Berkeley, in 1997, where he returned as an assistant professor in 1999. When he's not exploring theoretical possibilities beyond the Standard Model of particle physics, he enjoys hiking in the High Sierra and the California desert. Dimopoulos grew up in Athens, Greece, received a Ph.D. from the University of Chicago and has been a professor of physics at Stanford since 1979. His research has mostly been driven by the quest for what lies beyond the Standard Model. In 1981, together with Howard Georgi of Harvard University, he proposed the supersymmetric Standard Model. "Gia" Dvali grew up in what is now Georgia and in 1992 received his Ph.D. in high-energy physics and cosmology from Tbilisi State University. In 1998 he became an associate professor of physics at New York University. He enjoys overcoming gravity by high mountaineering and rock and ice climbing.

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An introduction to string theory is available at http://superstringtheory.com/

BRYAN CHRISTIE

Male Sexual Circuitry

by Irwin Goldstein
and the Working Group for the Study of Central Mechanisms in Erectile Dysfunction

Five hundred years ago Leonardo da Vinci made an observation about the penis that rings true even today for many men and their partners. The Renaissance scientist, inventor and artist—one in a long line of investigators who have attempted to solve the riddle of penile rigidity—observed that this seemingly wayward organ has a will of its own. "The penis does not obey the order of its master, who tries to erect or shrink it at will, whereas instead the penis erects freely while its master is asleep. The penis must be said to have its own mind, by any stretch of the imagination," he wrote.

Da Vinci, who dissected cadaverous penises from men who had been executed by hanging, was the first scientist to recognize that during an erection, the penis fills with blood. In his perception that the penis acts of its own free will, however, this multitalented scholar was wrong.

Far from having a mind of its own, the penis is now known to be under the complete control of the central nervous system—the brain and spinal cord. As William D. Steers, chair of the department of urology at the University of Virginia, has noted, any disturbance in the network of nerve pathways that connects the penis and the central nervous system can lead to erection problems.

In the past few decades the study of erections has been redefined. Thanks to advances in molecular biology, we now have a better understanding of the processes within the penis that lead to erection and detumescence, the return of the penis to a flaccid state. Armed with this knowledge, we have begun to explore how the brain and spinal cord control erections and other sexual functions. The field is still young, but we are optimistic that these efforts will lead to new therapies for the millions of men who suffer from sexual dysfunction—and we expect that some of these findings will also inform treatments for women. Although research on women has lagged far behind that on men, we are beginning to elucidate the striking similarities—as well as differences—between the sexes in regard to sexual function.

An erection is a carefully orchestrated series of events, with the central nervous system in the role of conductor. Even when the penis is at rest, the nervous system is at work. When a man is not sexually aroused, parts of the sympathetic nervous system actively limit blood flow to the penis, keeping it limp. The sympathetic nervous system is one of two branches of the autonomic nervous system—the part of the central nervous system that controls largely "automatic" internal responses, such as blood pressure and heart rate.

Dynamic Balance

Within the penis, and throughout the nervous system, a man's sexual response reflects a dynamic balance between excitatory and inhibitory forces. Whereas the sympathetic nervous system tends to inhibit erections, the parasympathetic system—the other branch of the autonomic nervous system—is one of several important excitatory pathways. During arousal, excitatory signals can originate in the brain, triggered perhaps by a smell or by the sight or thought of an alluring partner, or by physical stimulation of the genitals.

Regardless of where the signals come from, the excitatory nerves in the penis respond by releasing so-called proerectile neurotransmitters, including nitric oxide and acetylcholine. These chemical messengers signal the muscles of the penile arteries to relax, causing more blood to flow into the organ. Spongy chambers inside the penis fill up with blood. As these expand, they compress the veins that normally drain blood from the penis. This pressure squeezes the veins until they are nearly closed, trapping blood within the chambers and producing an erection. (Viagra—also known as sildenafil—works by slowing the breakdown of one of the chemicals that keeps the muscles relaxed, thereby holding blood in the penis.)

During an erection, the penis not only receives nerve signals but also sends them to the spinal cord and brain. The penis has an unusually high density of specialized tactile receptors; when these receptors are stimulated, their signals course to the spinal cord and brain, where they influence nerve pathways from these higher centers. So although the penis does not "think" for itself, it keeps the brain and spinal cord well apprised of its feelings. After a man climaxes or the arousal has diminished, the erection quickly subsides. The sympathetic nervous system again limits blood flow into the penis, which returns to its soft state.

Circumstances that increase the activity of the sympathetic nervous system—such as stress or exposure to cold—can temporarily shrink the penis by making it more flaccid. Conversely, switching off the activity of the sympathetic nervous system enhances erections. Nocturnal erections are a good example of this phenomenon. These occur primarily during rapid eye movement (REM) sleep, the stage in which dreaming occurs. During REM sleep, sympathetic neurons are turned off in the locus coeruleus, a specific area of the brain stem, the part of the brain that connects to the spinal cord. According to one theory, when this sympathetic brain center is quiet, proerectile pathways predominate, allowing nocturnal erections to occur. We often refer to such erections as "battery-recharging mechanisms" for the penis, because they increase blood flow, bringing in fresh oxygen to reenergize the organ. (Episodes of nocturnal arousal also occur in women. Four or five times a night—that is, during each episode of REM—women experience la-

ANCIENT GREEK HERM, or square pillar, from 510 B.C. illustrates the connection between the brain and the penis that has long mystified many and that is currently the subject of so much research.

GIRAUDON/ART RESOURCE

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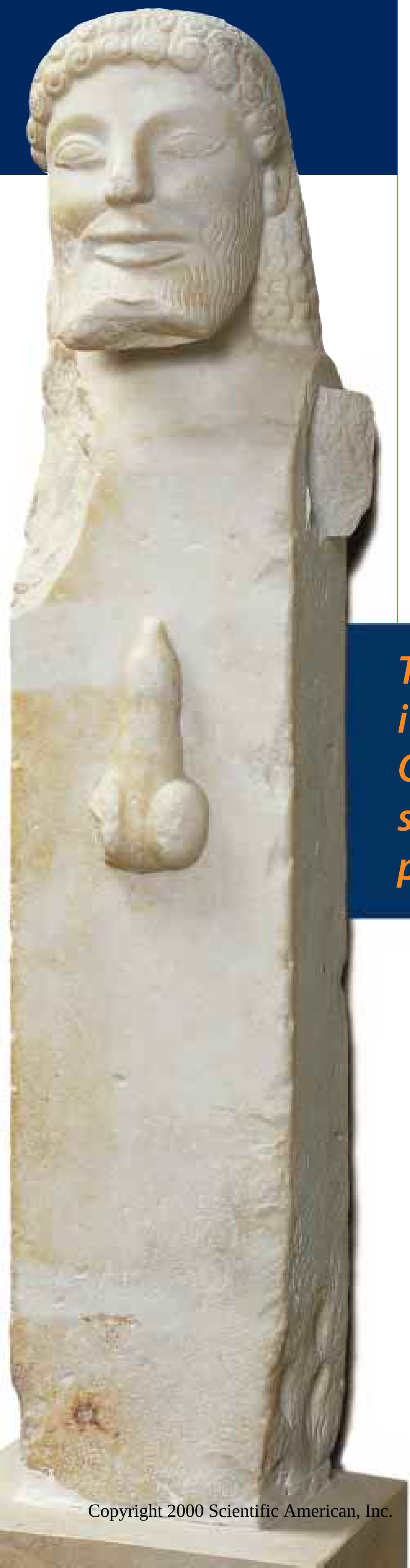


bial, vaginal and clitoral engorgement.)

Some erections, called reflexive erections, are generated entirely in the spinal cord. Much like touching a finger to a hot burner triggers a rapid withdrawal of the hand, physical stimulation of the penis can set off a spinal erection reflex in some situations. So crucial is reproduction to our perpetuation as a species that it appears that the capacity to create an erection has been wired into nerve circuits near the base of a man's spine.

In humans, most of the evidence for this finding has come from observations of soldiers with spinal cord injuries, particularly veterans wounded in World War II. Before then, the general belief was that men with spinal cord injuries were permanently and completely impotent and sterile. Although we now know that this view is mistaken, it is understandable. The spinal cord is the information superhighway for the nervous system, shuttling nerve stimuli to and from the brain and the peripheral nerves of the rest of the body. If the spinal cord is damaged, this flow of nerve impulses can be interrupted in myriad ways, depending on where the injury occurs and how extensive it is.

The brain is the most important sex organ. One of its roles in male sexuality is to keep the penis under control.

Yet, as physician Herbert Talbot reported in a classic study in 1949, men with severe or complete spinal cord injuries often continue to have erections. In his examination of 200 men with paraplegia, two thirds were able to achieve erections, and some were able to engage in vaginal intercourse and have an orgasm. Even though devastating war injuries left these men paralyzed and unable to control many basic bodily functions, the ability to have erections was often preserved.

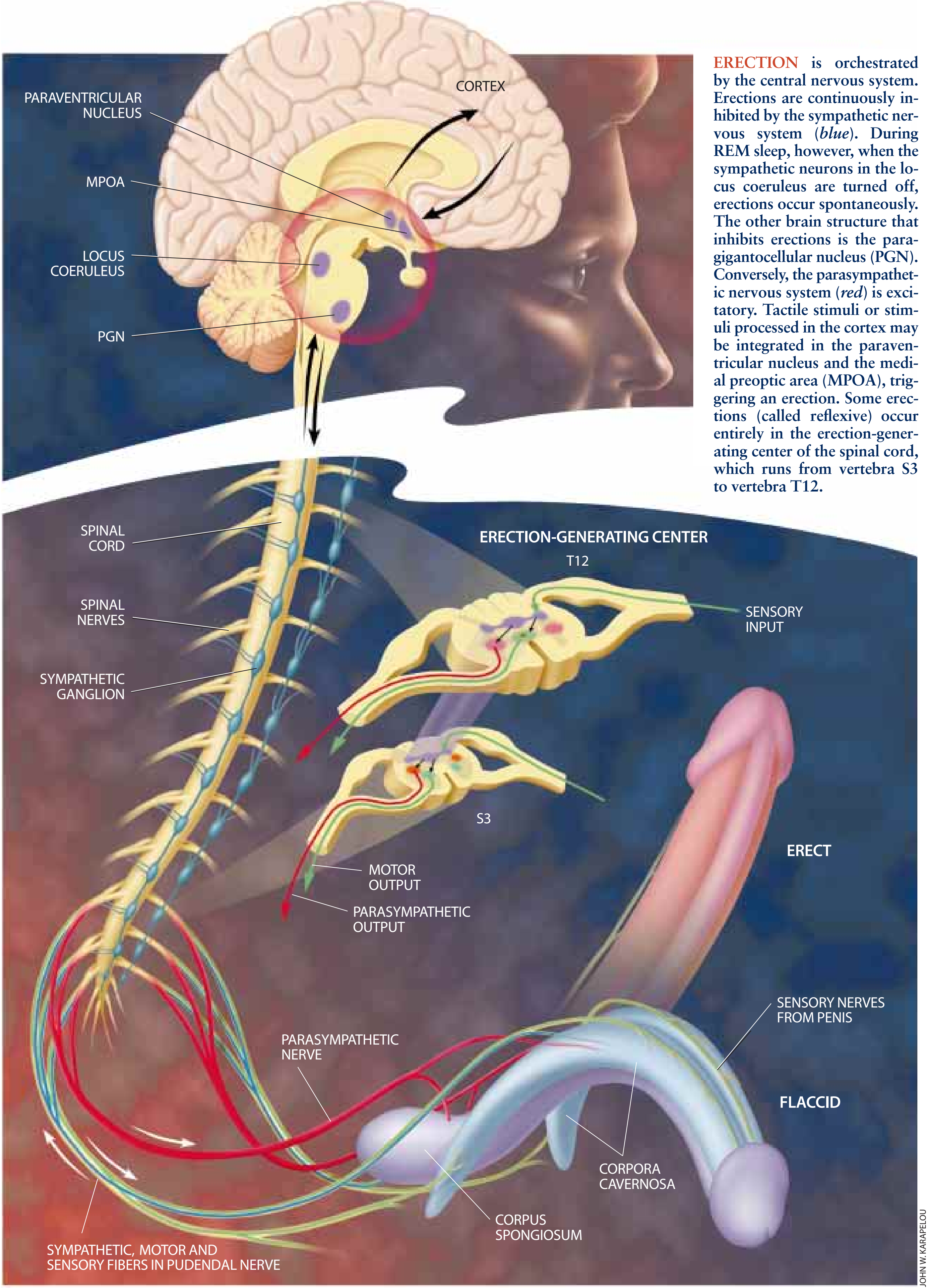
These observations—and information from studies in laboratory animals as far back as the 1890s—led to the discovery that an "erection-generating center" is located in the sacral segments of the spinal cord (that is, just above the tail end of the spine, between the S3 and T12 vertebrae). Physical stimulation of the penis sends sensory signals via the pudendal nerve to this erection center. The incoming signals activate connector nerve cells called interneurons, which then stimulate nearby parasympathetic neurons. These neurons send erection-inducing signals from the sacral spine to the penile blood vessels. As long as this reflex arc remains intact, an erection is possible.

The Brain's Brakes

Observations of men and laboratory animals with spinal cord damage have led to another intriguing finding: when the brain is disconnected from the erection-generating center in the spinal cord, erections typically occur more frequently and with less tactile stimulation than they did before the injury. For instance, Benjamin D. Sachs, an experimental psychologist at the University of Connecticut, found in 1979 that spinal transection in rats caused an increase of more than 1,000 percent in the number of erections and a 94 percent reduction in the time it took for the animals to become erect.

It seemed as if, in the disconnection of the brain from the body, some inhibitory control over erections was removed. This proved to be the case. In 1990 physiologists Kevin E. McKenna and Lesley Marson, then at Northwestern University, identified the brain center that keeps the brakes on spinal-mediated erections. They found that a specific cluster of neurons in the hindbrain (an evolutionarily ancient part of the brain that controls such basic functions as blood pressure and heart rate) is in charge of this central inhibition. When McKenna and Marson destroyed this group of neurons—called the paragigantocellular nucleus, or PGN—in a male rat's brain, the inhibition disappeared, causing more frequent and intense erections.

These researchers then made another significant discovery about the brain's role in suppressing erections. They found that the PGN neurons send most



ERECTION is orchestrated by the central nervous system. Erections are continuously inhibited by the sympathetic nervous system (*blue*). During REM sleep, however, when the sympathetic neurons in the locus coeruleus are turned off, erections occur spontaneously. The other brain structure that inhibits erections is the paragigantocellular nucleus (PGN). Conversely, the parasympathetic nervous system (*red*) is excitatory. Tactile stimuli or stimuli processed in the cortex may be integrated in the paraventricular nucleus and the medial preoptic area (MPOA), triggering an erection. Some erections (called reflexive) occur entirely in the erection-generating center of the spinal cord, which runs from vertebra S3 to vertebra T12.

of their axons down to the erection-generating neurons in the lower spinal cord. There the PGN nerve endings release the neurotransmitter serotonin—a chemical messenger that inhibits erections by opposing the effects of proerectile neurotransmitters.

This discovery may have important implications for the millions of men and women who take serotonin-enhancing drugs to treat depression and other mental health problems. Drugs such as Prozac and Paxil, which belong to the widely used class of drugs called selective serotonin reuptake inhibitors (SSRIs), work in part by increasing brain levels of serotonin. These drugs often cause sexual dysfunction as an unwanted side effect, most commonly delayed or blocked ejaculation in men and, in women, reduced sexual desire and difficulty reaching orgasm.

The work of McKenna and his colleagues provides an explanation for how this side effect may occur. By increasing serotonin in the central nervous system, SSRIs may tighten the brain's built-in brakes on erection, ejaculation and other sexual functions in some people.

As often happens in medicine, however, one person's side effect can be another's therapy. The inhibitory properties of SSRIs have been shown to be helpful for men with premature ejaculation, a condition in which a man climaxes too quickly, typically before vaginal penetration or a few seconds thereafter. SSRIs are effective in delaying orgasm in these men, most likely because they increase central inhibition. Although more research is needed, SSRIs may also hold promise in treating sexual disorders that are associated with excessive or inappropriate sexual urges, such as paraphilias—for example, pedophilia, a sexual interest in children.

Considering that sex makes the world go 'round, or at least keeps us on the planet, it is not clear why these elaborate inhibitory controls have evolved. Although no one knows for sure, some intriguing theories have been advanced. John Bancroft of Indiana University believes that for most men this central inhibition is adaptive, keeping them out of trouble that might arise from excessive or risky pursuit of sexual enjoyment. These internal brakes also may help prevent a man from having repeated ejaculations during sexual encounters, which could lower his sperm store and reduce fertility.

Also, as with many pleasures in life, an erection can become too much of a good thing if it lasts too long. An erection that persists longer than four hours—a phenomenon that may occur in men with sickle cell anemia and in those who use certain drugs—is considered a medical emergency. Called priapism, this condition traps blood within the erect penis, leading to permanent damage if not treated promptly: if freshly oxygenated blood is not brought in, tissue starvation can occur.

Despite the benefits of central inhibition for most men, Bancroft believes it can cause problems for others if it is too strong or too weak. If a man has too much central inhibitory control—if, say, his brain serotonin levels are too high—he may develop sexual dysfunction. Conversely, if his central inhibition is too low, he may be more inclined to engage in high-risk sexual behaviors, such as recklessly ignoring the threat of sexually transmitted diseases in the pursuit of sexual gratification.

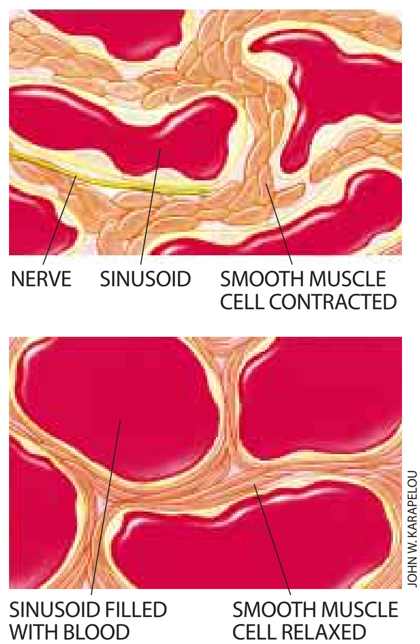
Inside the Brain

Many regions throughout the brain contribute to the male sexual response, ranging from centers in the hindbrain, which regulates basic body functions, to areas of the cerebral cortex, the organ of higher thought and intellect. The brain sites we have identified so far appear to be extensively interconnected. We now think the brain's control of sexual function works as a unified network, rather than as a chain of relay sites. In other words, the control of erection does not appear to be organized in a tightly linked chain of command centers but rather is distributed throughout multiple areas in the brain and spinal cord. Therefore, should injury or disease destroy one or more of these regions, the capacity for erections often remains intact.

One of the important brain regions regulating sexual behavior is the hypothalamus. This small area plays a vital role in linking the nervous and endocrine, or hormonal, systems and is involved in the control of certain basic behaviors, such as eating and aggression. A cluster of neurons in the hypothalamus, called the medial preoptic area, or MPOA, seems to have a crucial role in sexual function and, accordingly, is being intensively studied at the moment.

Researcher François Giuliano of the Faculté de Médecine of the Université Paris-Sud and his colleagues have recently shown that electrical or chemical stimulation of the MPOA causes erections in rats. The MPOA appears to integrate stimuli from many areas of the brain, helping to organize and direct the complex patterns of sexual behavior. Some scientists speculate that the MPOA may also be involved in the recognition of a sexual partner.

The hypothalamus also contains the paraventricular nucleus, another group of neurons with an important role in male sexual function. Like the MPOA, this nucleus is a processing center that sends and receives messages from different parts of the brain and spinal cord. During sexual arousal, the paraventricular nucleus releases oxytocin. This hormone has long been known to stimulate the release of milk in breast-feeding women and uterine contractions during delivery of a baby; in many species, oxytocin is a chemical "love" messenger that promotes bonding and social attachments. But it also proves to be a brain neurotransmitter that has a powerful proerectile effect in men. Like other neurotransmitters, oxytocin binds to target neurons and regulates the con-



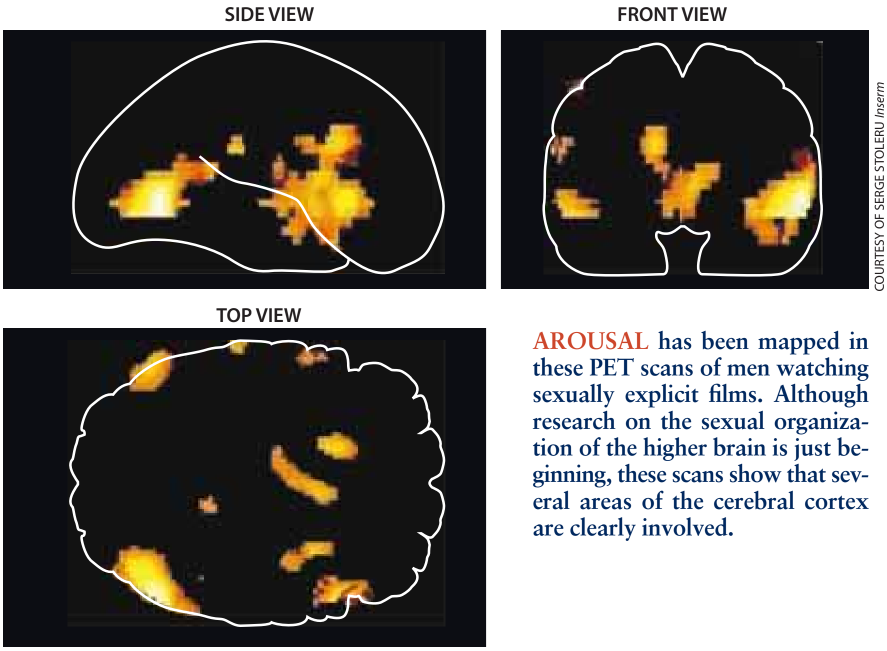
ENGORGEMENT begins when nerves release transmitters that diffuse into the smooth muscle cells around the arteries in the penis, causing the normally contracted cells to relax and blood to flow in (*top*). As they relax, the muscles elongate, pushing against the veins that drain blood from the penis. The blood becomes trapped in sinusoids—the chambers between muscle cells—and the penis becomes erect (*bottom*).

duction of nerve impulses. In this case, oxytocin activates excitatory nerve pathways running from the spinal erection-generating center to the penis.

Higher brain centers are involved in male sexual response as well, but we know much less about them. Nevertheless, the few studies to date have provided some intriguing results. Researcher Serge Stoleru of Inserm in Paris recently used positron emission tomography (PET) to reveal which parts of the cerebral cortex are activated when men are sexually aroused. He compared PET scans in a group of men who were presented with three kinds of films: sexually explicit, humorous and emotionally neutral (such as a documentary on the Amazon). Stoleru found that when men were sexually aroused, specific parts of the cerebral cortex were activated, including regions associated with emotional experiences and control of the autonomic nervous system.

In addition, scientists are exploring how higher brain functions, such as memory and learning, help to control erections. Psychologist Raymond Rosen of Robert Wood Johnson Medical School in New Brunswick, N.J., showed that healthy men can be taught to have erections on demand, in response to mental imagery or nonsexual cues. In one study, men were instructed to use their minds to arouse themselves in exchange for a financial reward. When they were given feedback on their performance via a light display, they rapidly learned to increase their erections—in the absence of direct physical stimulation—through the use of imagery and fantasy techniques. To keep their motivation high, the men earned financial bonuses that depended on the number and degree of erections they achieved.

This experiment was one of many that have shown that learning and memory strongly influence erections. Indeed, the ability of the brain to associate sexual arousal and orgasm with cues helps to explain why an astounding number of fetish objects—such as high-heeled shoes, leather whips and lingerie—can often enhance sexual arousal.



AROUSAL has been mapped in these PET scans of men watching sexually explicit films. Although research on the sexual organization of the higher brain is just beginning, these scans show that several areas of the cerebral cortex are clearly involved.

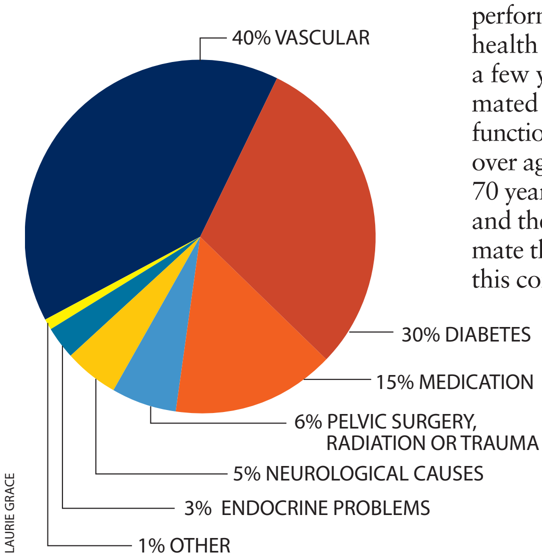
When Things Go Wrong

By understanding the role of the central nervous system in controlling erection and other sexual functions, we hope to set the stage for new therapies. Erectile dysfunction, which is defined as a consistent inability to get or keep an erection that is satisfactory for sexual performance, is an increasingly common health problem. A study we conducted a few years ago in the Boston area estimated that some degree of erectile dysfunction affects about 40 percent of men over age 40 and up to 70 percent of men 70 years old. As baby boomers grow old and the global population ages, we estimate that the number of men who have this condition will more than double in the next 25 years—ultimately affecting more than 330 million men worldwide.

If nerve stimuli cannot reach the penis for any reason, an erection problem is inevitable. Such dysfunction can also be an unfortunate complication of surgery to remove the prostate gland to treat prostate cancer, because this procedure can damage penile nerves. Diabetes can lead to nerve and blood vessel damage in the penis as well. Many neurological conditions—including spinal cord injury, Parkinson's disease, multiple sclerosis and stroke—can cause problems. And because a man's moods and mental well-being affect the flow of nerve messages to the penis, it is not surprising that stress, depression, anxiety or anger often underlies erection difficulties.

Using their growing knowledge of central nervous system control, researchers have begun to develop medications that target the central nervous system. A drug called apomorphine will most likely be the first in a new generation of therapies that acts directly on the brain as opposed to the penis, as Viagra does. Apomorphine—brand name Uprima—mimics the neurotransmitter dopamine, enhancing erections by binding to specific receptors on nerve cells in the paraventricular nucleus and the MPOA, thereby turning on proerectile pathways.

Apomorphine is under review by the U.S. Food and Drug Administration for



ERECTILE DYSFUNCTION has many causes, ranging from stress and other psychological concerns to purely physiological factors. This chart depicts the main physical causes of dysfunction and reveals that vascular problems underlie a vast number of cases.

approval, and a final decision is expected soon. Although the compound has been used in medicine for more than a century—for the treatment of Parkinson's disease, among other disorders—it was not until the mid-1980s that investigators, including R. Taylor Segraves, a psychiatrist at Case Western Reserve University, and Jeremy P. W. Heaton, a urologist at Queen's University in Ontario, began investigating it for the treatment of erectile dysfunction. Since then, clinical studies have evaluated apomorphine in more than 3,000 men and found that it can successfully treat those with many different types of erectile dysfunction.

Like all drugs, apomorphine can cause unwanted side effects. Whereas Viagra, the most widely prescribed drug for erectile dysfunction, can give rise to headaches, nasal stuffiness and facial flushing, apomorphine can induce nausea during its initial use. In the future, we may be able to treat some men more effectively by combining apomorphine with therapies that act directly on the penis.

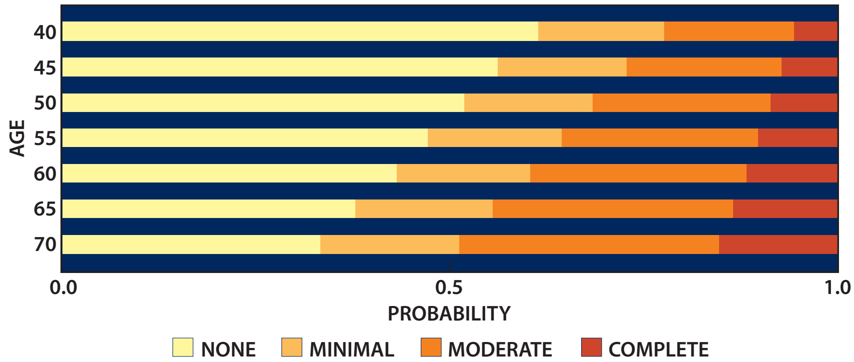
Sex and the Sexes

Until recently, most research on sexual function focused in large part on men and the control of penile erection. Fortunately, this is changing, as we increasingly recognize that sexual dysfunction is extremely common—and treatable—in both sexes. In fact, a recent survey of more than 3,000 Americans reported that the number of women with sexual complaints was greater than the number of men: 43 percent as opposed to 31 percent.

Many researchers are studying the mechanisms that control sexual function in women and are testing therapies to treat female sexual disorders. Our laboratory is conducting a clinical trial to determine whether apomorphine can enhance sexual arousal in women with such problems. We also are testing a new FDA-approved device called the EROS-Clitoral Therapy Device, which is used to provide gentle suction to the clitoris, causing engorgement. In women with sexual dysfunction, it has been shown to safely improve sexual sensation, lubrication, orgasm and sexual satisfaction.

This research has made us aware of some similarities between the sexes in the central nervous system's control of arousal, orgasm and various sexual functions. Preliminary evidence suggests that the central control of sexual function in men and women is remarkably similar. For instance, as noted earlier, both sexes experience nocturnal arousal responses, and both are vulnerable to SSRI-induced sexual dysfunction.

Of course, there are also dramatic differences—as in the postorgasmic refractory period, the normal delay after an orgasm before arousal can occur again. Women can have multiple orgasms and therefore have virtually no refractory period, but most men have a refractory period that lasts from several minutes to many hours.



IMPOTENCE increases with age, according to several surveys. In 25 years, given the aging of the world's population, it is estimated that the condition may affect more than 330 million men.

We have come a long way since da Vinci's discovery that the penis fills with blood—not air or spiritual essences—during an erection. The past decade has revolutionized not only the field of erection research but also our societal attitudes about sexual health. Only a few years ago erectile dysfunction went generally untreated.

Today this condition and other sexual problems are more openly recognized and discussed. Millions of men are receiving care for erection troubles, thanks to a burgeoning appreciation of the importance of sexual health and the availability of more effective and convenient treatments. In the near future we anticipate that there will be an even wider array of therapies for men and women. With our increasing insight into the brain's role in controlling our sexuality, we are also moving toward a more holistic view of sexual well-being—one that integrates mind and body and responds to the unique needs of both sexes. SA

The Authors

IRWIN GOLDSTEIN is a urologist at Boston University. He is a member of the Working Group for the Study of Central Mechanisms in Erectile Dysfunction, which was formed in 1998. The other members are John Bancroft of Indiana University; François Giuliano of the Faculté de Médecine, Université Paris-Sud; Jeremy P. W. Heaton of Queen's University, Ontario; Ronald W. Lewis of the Medical College of Georgia; Tom F. Lue of the University of California, San Francisco; Kevin E. McKenna of Northwestern University; Harin Padma-Nathan of the University of Southern California; Raymond Rosen of the Robert Wood Johnson Medical School; Benjamin D. Sachs of the University of Connecticut; R. Taylor Segraves of Case Western Reserve University; and William D. Steers of the University of Virginia. All the authors consult or investigate (or have done so in the past) for one or more pharmaceutical companies—among them Abbott, Eli Lilly, Merck, Pfizer and TAP; Sachs owns stock in Abbott; Heaton shares several patents on apomorphine.

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Birth of the

Modern Diet

Ever wonder why dessert is served after dinner? The origins of modern Western cooking can be traced to ideas about diet and nutrition that arose during the 17th century

by Rachel Laudan

Were we to attend a 16th-century court banquet in France or England, the food would seem strange indeed to anyone accustomed to traditional Western cooking. Dishes might include blancmange—a thick puree of rice and chicken moistened with milk from ground almonds, then sprinkled with sugar and fried pork fat. Roast suckling pig might be accompanied by a cameline sauce, a side dish made of sour grape juice thickened with bread crumbs, ground raisins and crushed almonds, and spiced with cinnamon and cloves. Other offerings might consist of fava beans cooked in meat stock and sprinkled with chopped mint or quince paste, a sweetmeat of quinces and sugar or honey. And to wash it all down, we would probably drink hypocras, a mulled red wine seasoned with ground ginger, cinnamon, cloves and sugar.

Fast-forward 100 years, though, and the food would be reassuringly familiar. On the table might be beef bouillon, oysters, anchovies and a roast turkey with gravy. These dishes might be served alongside mushrooms cooked in cream and parsley, a green salad with a dressing of oil and vinegar, fresh pears, lemon sherbet, and sparkling white wine.

Before 1650, the elite classes throughout the Islamic and Christian worlds from Delhi to London shared pretty much the same diet: thick purees, lots of spices, sweet and sour sauces, cooked vegetables, and warmed wines. Sugar was ubiquitous as a seasoning in savory dishes. But in the middle of the 17th century, the northern European diet began to change. This new regimen relied on fewer spices, based its sauces on fats such as butter and olive oil, and incorporated raw fruits and vegetables. Sugar appeared only at the end of a meal.

What happened? Economic considerations cannot account for the difference: for the upper class, money was no object. For the poor, both meals would have been far out of reach. Well into the 19th century, they subsisted on vegetable soups and gruels with bread or porridge. Novel foodstuffs from the New World do not explain the shift in diet either, because with the exception of turkey, the dishes at the second banquet depended not on new ingredients but on new uses of long familiar ones. The clue to this transformation in eating habits between the 16th and 17th centuries must be sought instead in evolving ideas about diet and nutrition—which is to say, in the history of chemistry and medicine.

Medicine in the 16th Century

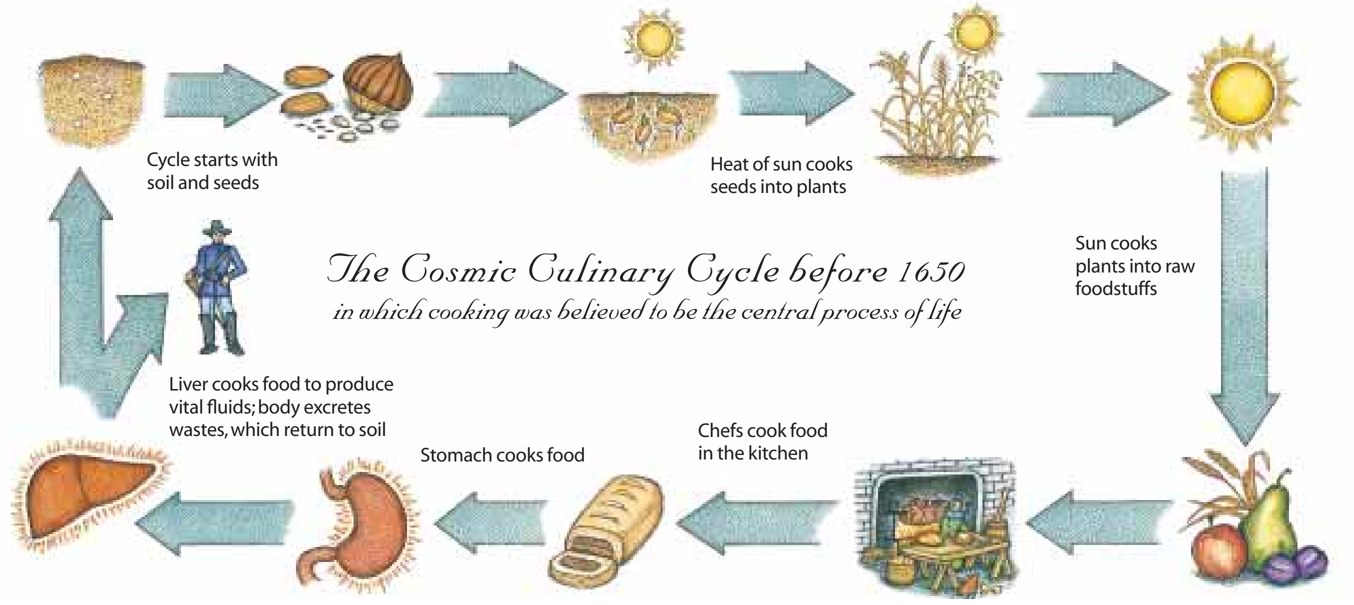
Eating healthy food was extremely important to people of earlier eras, perhaps even more so than it is today. Activity in the kitchen mattered so much because physicians had so few other options. To avoid resorting to unpleasant therapies such as purging or bloodletting, doctors carefully monitored their wealthy patients' daily habits: their emotional state, for example, or how much sleep, exercise and fresh air they got. Most crucially, doctors advised their patients on the food and drink they should consume. Every court had a bevy of physicians who were schooled in the physiology of digestion, the nutritive properties of foodstuffs and the nature of a healthy meal. Offering dietary advice to their affluent patrons was a major part of their work.

The actual task of transforming abstract dietary theory into dishes appropriate for the courtly table fell to the head chefs, or majordomos, as they were often called. In a popular medical text written in 1547, *Breviary of Health,* author Andrew Boorde noted, "A good coke is halfe a physycyon." Sixteenth-century cooks, physicians and their patrons shared a common notion of diet and nutrition that can be traced to classical antiquity. First formulated around 400 B.C. as part of the Hippocratic Collection, the ideas were systematized by the great Roman doctor Galen in the early second century A.D. After the collapse of classical civilization, Islamic intellectuals eagerly took up these notions (along with many other scientific theories of the ancient world).

By the 12th century, European scholars had translated key Arabic texts into Latin; teachers at the major medical schools, such as Montpellier in the south of France, relied extensively on these texts. In the late 15th century, experts began translating newly discovered Greek manuscripts as well as retranslating known texts. These documents formed the basis of a host of popular manuals and mnemonic jingles. Particularly well liked were the numerous vernacular variations on a Latin poem, the *Regimen Sanitatis Salernitanum,* apparently composed around the end of the 11th cen-

SUMPTUOUS SPREAD from the 16th century might have included blancmange (a puree of rice and chicken) and a side dish of cameline sauce (made of crushed almonds, bread crumbs and spices moistened with sour grape juice), accompanied by mulled red wine, or hypocras. By the 17th century the foods looked more familiar to the modern eye: roast turkey, green salad with oil and vinegar dressing, and sparkling white wine.

HEIDI NOLAND



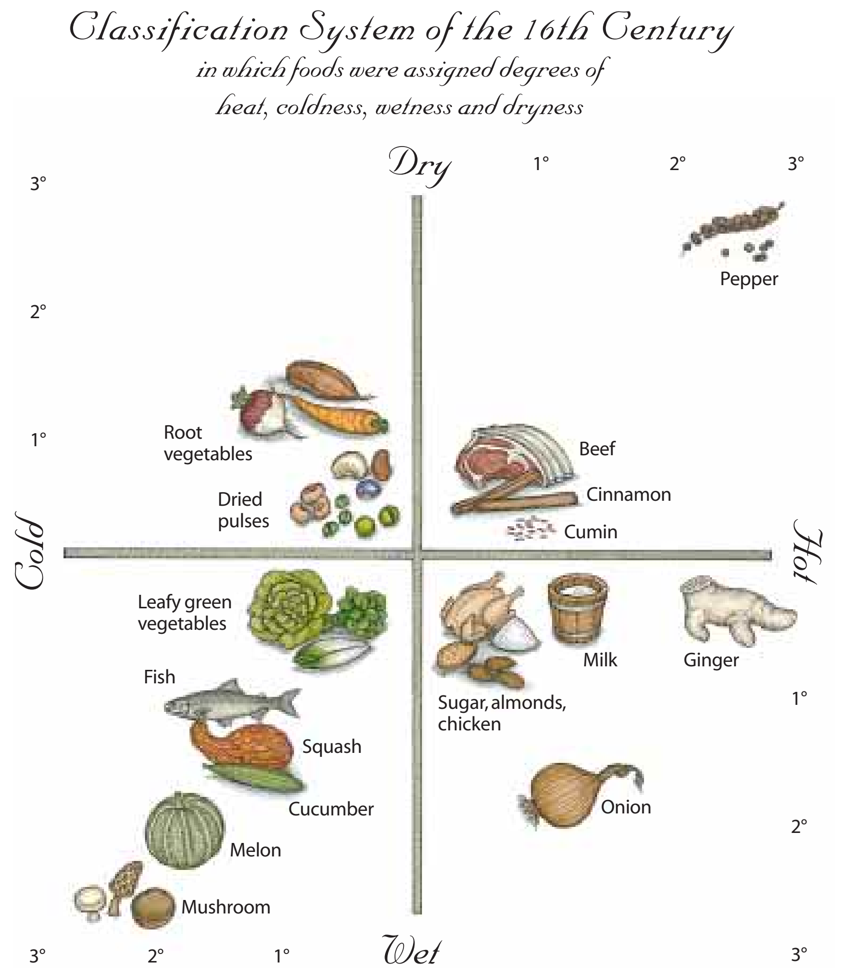
tury but still widely circulated in the 16th and even 17th centuries:

Peaches, apples, pears, milk,
cheese, and salted meat,
Deer, hare, goat, and veal,
These engender black bile and are
enemies of the sick

The prevailing dietary wisdom of the 16th century, as presented in these medical guidebooks, relied on two assumptions: first, that the process of digesting foods was actually a form of cooking. Indeed, cooking stood as the basic metaphor for the systems that sustained all life. Seeds were cooked into plants; when the plants appeared above the ground, the heat of the sun cooked them into ripe fruits and grains. If humans gathered these foodstuffs, they could cook them further to create edible dishes. Finally, the internal heat of the body turned the food into blood. The body then expelled as feces what was not digestible. Excrement joined putrefying dead animals and plants to begin the life cycle again.

The second assumption about food and health in this scenario involved maintaining a proper equilibrium of bodily fluids by eating a suitably balanced diet. Doctors and chefs of the time believed that four fluids, or humors, circulated in the body: blood, phlegm, yellow bile and black bile. These humors corresponded to the four Aristotelian elements—air, water, fire and earth. Because blood was hot and moist, it corresponded to air; phlegm was cold and moist and thus resembled water; yellow bile was hot and dry, similar to fire; black bile was cold and dry, connected to earth.

Ideally, the human body was slightly warm and slightly moist, although in practice the exact balance varied from individual to individual, depending on variables such as age, sex and geographic location. Older people were believed to be colder and drier than younger ones; menstruating women colder and wetter than men; southern Europeans more hot-blooded than their neighbors to the north. The perfect meal, like the perfect human temperament, was slightly warm and slightly moist, but combinations away from this center could be used as mild dietary correctives to warm and moisten the elderly, dry out the moister sex, and calm down the southerner or perk up the northerner.



ILLUSTRATIONS BY PATRICIA J. WYNNE

The majordomo, then, had the challenge of selecting and preparing meals adjusted to the temperament of the eater. The properties of any given food item were common knowledge: pepper, for example, was hot and dry in the third degree, and vinegar was cold and wet in the second degree. Root vegetables such as turnips were by nature earthy—dry and cold—and thus better left to peasants. If chefs should decide to prepare them, however, they would make sure to stew them, thereby adding warmth and moisture. In contrast, chard, marrow (a watery, squashlike vegetable) and especially onions were very wet and had to be fried.

Other foods were completely unacceptable: Guy Patin, a doctor at the University of Paris and author of *Treatise on the Conservation of Health,* published in 1632, cautioned that mushrooms, being cold and wet, should be avoided entirely. Melons and other fresh fruit were not much better, being very moist and liable to putrefy. In general, though, cooking not only helped achieve proper culinary balance—dry foods were boiled, wet foods fried or roasted—but the process also, in effect, partially predigested the foods, making them easier for the body to assimilate.

According to these medical theories, the blancmange on our 16th-century table was close to perfect. The wise chef had combined chicken, rice and almond milk, all slightly warm and moist, and the sugar on top—also warm and moist—was the crowning touch. The naturally moist suckling pig had been roasted. The cameline sauce balanced cool, moist vinegar with the warmth of raisins and hot, dry spices. The chef was careful not to serve quinces and grapes fresh, and hence dangerously cold and moist, but instead offered them dried or cooked with added sugar (in the quince paste).

Health experts viewed wine with a meal as an ideal nutrient—provided, of course, that diners did not drink to excess. *The Book of Wine,* written around 1310, printed in 1478 and widely attributed to Arnald of Villanova (a leading medical writer and physician to James II of Aragon), had only high praise for the beverage: besides being good for flatulence and infertility, wine "fortifies the brain and the natural strength … causes foods to be digested and produces good blood." Even so, because red wine tended to be cold and dry, chefs often served it warm with added sugar and spices, creating hypocras. With these options before them, the members of the 16th-century court could rest assured that they were getting a healthy meal.

17th-Century Cooking

By the middle of the 17th century, however, physicians of a quite different persuasion began to join the courts of northern Europe. These scholars derived their ideas from Paracelsus, an itinerant doctor from Germany who, in the 1520s, began to mock the structure of classical medicine. Paracelsus's abrasive personality and radical religious beliefs gave him a dreadful reputation, so few physicians admitted to this heritage. But acknowledged or not, the link was clear: these court doctors argued, as Paracelsus had, that the idea of a cosmic life cycle based on cooking and the Aristotelian elements was wrong and had to be revised.

Historians of science still debate the causes of this shift, but the technology of distillation seems to have contributed to it. As the practice became more important from the late Middle Ages on, chemists experimented with heating a great variety of natural substances, many of them edible, such as fennel, nutmeg and cloves. They noted that in every case the original material separated into three parts: a volatile, or "spirituous," fluid; an oily substance; and a solid residue.

Drawing on such observations, these chemists proposed three new elements in place of Aristotle's four: mercury (the essence of the vaporous fluids; not related to the toxic chemical of the same name), sulfur (the essence of the oily substances; again, unrelated to the chemical) and salt (the essence of the solids; not the same as modern table salt). In such a scheme, salt dictated the taste and consistency of foods. Mercury was the source of smells and aromas. Sulfur, or oil, carried the properties of moistness and sweetness; it also bound together the other two, normally antagonistic, elements.

Physicians of this era also believed that digestion involved fermentation rather than cooking, and they began to investigate the familiar yet mysterious process more closely. Because fermentation included gentle heat and the production of vapors, it seemed to resemble (or was possibly the same as) putrefaction, distillation, and the interaction of acids and salts. Vapors, spirits or airs (soon to be dubbed "gases" by Dutch scientist and mystic Johannes Baptista van Helmont)

Typical Pre-17th-Century Recipes

Cameline Sauce

"To make an excellent cameline sauce, take skinned almonds and pound and strain them; take raisins, cinnamon, cloves and a little crumb of bread and pound everything together, and moisten with verjuice; and it is done."*

**sour juice of unripe grapes*

Blancmange

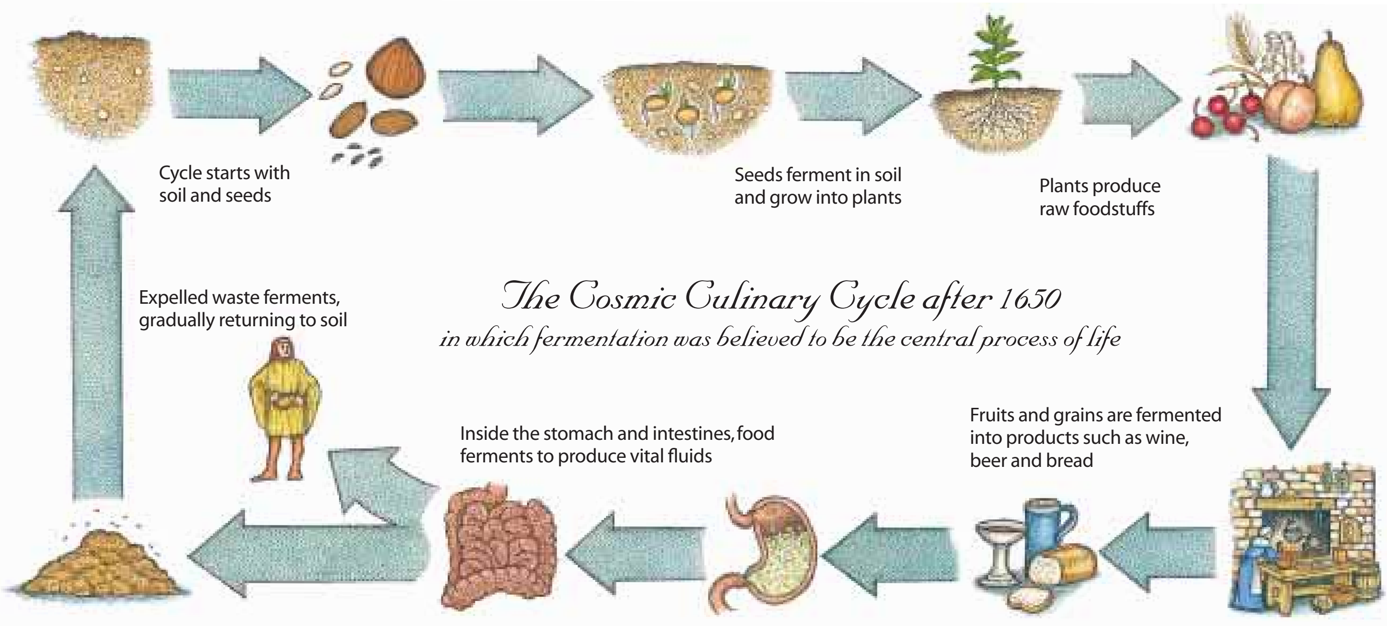
"Take cooked breasts of chicken and put them on a table and shred them into the finest fibers you can. Then wash the rice and dry it, and make it into flour, and put it through a sieve; then moisten this rice flour with goat's, sheep's or almond milk, and boil it in a well-washed and clean pan; and when it begins to boil, add those shredded breasts, with white sugar and fried white pork fat; and keep it away from the smoke, and let it boil gently without excessive fire, so that it becomes as thick as the rice should be. And when you serve it, top it with crushed or pounded sugar, and fried pork fat."

Hypocras

"To make a lot of good hypocras, take an once of cinamonde, known as long tube cinnamon, a knob of ginger, and an equal amount of galangal, pounded well together, and then take a livre of good sugar; pound this all together and moisten it with a gallon of the best Beaune wine you can get; and let it steep for an hour or two. Then strain it through a cloth bag several times so it will be very clear."*

**a root in the ginger family*

SOURCE: The Medieval Kitchen: Recipes from France and Italy, *University of Chicago Press, 1998.*



excited chemists of the time, as they appeared to be the very essence of the substance from which they originated.

Several prominent physicians of the 17th century advocated this new understanding of digestion, among them van Helmont, Franciscus Sylvius, a physician at the University of Leiden, and Thomas Willis, then the best-known doctor in England and a founding member of the Royal Society of London. According to this view, digestion involved the fermenting, rather than the cooking, of foodstuffs. Gastric juices, considered acid and sharp, acted on foods to turn them into a white, milky fluid, which then mixed with alkaline bile in the digestive tract. The mixture fermented and bubbled, producing a salty substance that the body could transform into blood and other fluids.

Like their 16th-century predecessors, these later physicians presented a cosmic cycle of life that reflected their view of digestion. Seeds became plants as a result of the "ferments of the earth," in the words of John Evelyn, a keen horticulturist who spoke before the Royal Society in 1675. Fermentation turned grains and fruits into bread, beer and wine, which the digestive system could ferment further. Putrefaction of waste material started the cycle all over again. "Vegetable putrefaction resembles very much Animal Digestion," stated John Arbuthnot, member of the Royal Society and physician to Queen Anne, in a popular handbook on foodstuffs that appeared in 1732. The cosmos was still a kitchen but was now equipped with brewers' vats, and the human body held miniature copies of that equipment.

These changes in the understanding of the digestive process put 17th-century chefs on guard. Alert cooks seized the opportunity to establish their good reputations by thinking up dishes that were healthful by the new standards—and, of course, also tasty. For instance, chefs welcomed oysters, anchovies, green vegetables, mushrooms and fruits because they fermented so readily and thus did not need complicated preparation in the kitchen to be predigested. As cooks began to incorporate fresh produce into many of their dishes, horticulture and botanical gardens became the rage. Scientists and scholarly gentlemen exchanged seeds, translated gardening books and developed hothouses for tender vegetables. They began cultivating mushrooms on beds of putrefying dung. In England, the well-to-do put even such previously distasteful dishes as eggplant on their tables.

The First Restaurants

Substances rich in oil, such as butter, lard or olive oil, all with the useful property of binding the components of salt and mercury, became the basis of a variety of sauces. They were combined with ingredients containing the element salt, such as flour and table salt, and others high in mercury, such as vinegar, wine, spirits, and essences of meat or fish. The first recipe for roux, a combination of fat and flour moistened with wine or stock to produce a single delicious taste, appeared in the cookbook *The French Chef,* written in 1651 by François Pierre de la Varenne. Salads, which combined oil-based dressings and readily digestible greens, also became quite fashionable. (Evelyn promoted vinaigrette salad dressing in his *Acetaria: A Discourse of Sallets,* published in 1699.)

As fruits, herbs and vegetables assumed a more prominent place in the main meal, sugar, formerly lauded as a panacea, came in for rough treatment at the hands of the chemical physicians. Some wanted to banish it altogether. "Under its whiteness," hissed Joseph Duchesne, physician to Henry IV of France, in 1606, "sugar hides a great blackness"—doctors knew that it blackened the teeth—"and under its sweetness a very great acrimony, such that it equals agua fortis [nitric acid]."

British physician Willis, who had noticed the sugary urine of patients suffering from what doctors later termed diabetes, concurred. "Sugar, distilled by itself, yields a liquor scarcely inferior to aqua fortis.... Therefore it is very probable that mixing sugar with almost all our food, and taken to so great a degree, from its daily use, renders the blood and humours salt and acrid; and consequently scorbutic."

The moral was clear: sugar was dangerous, perhaps even a poison. Such dire warnings would surely have given any chef second thoughts about sprinkling it over the main dishes of the meal, leaving the diner no choice but to eat it. Thus, sugar moved to the periphery of the menu, served only in desserts, which were prepared in a separate kitchen. Sugar became the subject of a distinct genre of books dedicated to its decorative, not medical, properties.

Physicians regarded alcoholic spirits and other distilled essences as useful medicines. They and their patients, though, considered a cordial or an eau-

The Three Principles

by which foods were classified in the late 17th century

The Sulfur Principle

Makes food oily, binds foods high in salt and mercury (oil, butter, lard)

The Salt Principle

Gives food taste (salt, flour)

The Mercury Principle

Makes food volatile or gaseous, gives it smell (vinegar, wine, meat essence)

ILLUSTRATIONS BY PATRICIA J. WYNNE

de-vie fine for the occasional sip but too strong for everyday use. Less powerful extractions, made from nutritive foods such as meats that had been concentrated by boiling or fermenting, could be more easily digested. Sometimes the concentrated goodness of a food even showed up as desirable gas bubbles that nourished the brain. Sparkling mineral waters gained immense popularity as spas opened across Europe. At the table, hot and spicy hypocras yielded to cool wines, even to sparkling champagne, which was most likely first produced in the late 17th century.

Chefs made essences of meat or fish from the "musculous Flesh, which is of all [parts of the animal] the most nourishing, that which produces the best juice," and then served this healthy fare in the form of stock, bouillon or jellies made from these liquids. Land animals had more nutritious juices than fish or birds did, and of the land animals, beef produced the most restorative ones. By 1733 Vincent la Chapelle, a French chef who worked for the earl of Chesterfield in England, had a variety of recipes for delicately garnished beef bouillon in his book *The Modern Cook,* which was quickly translated into French. Before long, entrepreneurs saw an opportunity in this new cuisine, selling "restaurants"—which is French for "restoratives"—to those who could not afford their own chefs.

Eventually Europe's middle classes emulated the aristocracy, developing a taste not only for restaurants but for all the new cuisine. Such foods seemed to offer a certain refinement, not just in the sense of good taste but also in a chemical sense, as the meals represented the most enhanced form of food. As the authors of the gastronomic treatise *The Gifts of Comus,* published in Paris in 1739, put it: "Modern cookery is a kind of chemistry. The cook's science consists today of analyzing, digesting, and extracting the quintessence of foods, drawing out the light and nourishing juices, mingling and blending them together."

This new diet gradually spread across Europe as it simultaneously made its way down the social scale. By the mid- to late 19th century it had become the standard for the English- and French-speaking worlds in Europe, the U.S., Canada and Australia. Other regions, however—the Islamic world and Spanish-speaking parts of the Americas, for example—remained isolated from the chemistry derived from Paracelsus and adopted neither the dietary theory nor the resultant cuisine. (The modern curries of India and moles of Mexico, for instance, resemble the cuisine of pre-Paracelsian northern Europe.)

The Western cuisine born in the 17th century long outlived the dietary theory that inspired it. By the end of the 18th century, chemists and physicians had embarked on the research that was to lead to the modern theories of the role of calories, carbohydrates, proteins, vitamins and minerals in the biochemical processes of digestion. Notably, during the 19th and early 20th centuries, when most of these studies were carried out, nutritionists focused on developing a cheap but adequate diet for factory workers, soldiers and other less affluent people. The shift of emphasis in the medical community from the rich to the poor, though, meant that chefs catering to the well-heeled continued to develop Western cuisine along the lines established in the 17th century.

Now that almost everyone in the West can afford the cuisine formerly restricted to the wealthy, we have come to realize that its dietary foundations are a mixed blessing. Although fresh fruit and vegetables score high marks, the centrality of fat in our diets (a result of the importance given to meat and fat-based sauces) is blamed for the high rates of obesity in most developed nations. In response, everyone from physicians to chefs has returned attention to the age-old problem of developing a new cuisine, at once delicious and in line with the latest findings in physiology and nutrition. SA

The Author

RACHEL LAUDAN received her doctorate in history and philosophy of science from the University of London. She has taught history of science and technology at Carnegie Mellon University, the University of Pittsburgh, Virginia Polytechnic Institute and State University, and the University of Hawaii. Laudan is the author of *From Mineralogy to Geology: The Foundations of a Science 1650–1830* (University of Chicago Press, 1987) and winner of the Jane Grigson prize for food scholarship of the Julia Child Cookbook Awards. She now lives in Mexico, where she is working on a book about the history of diet, to be published by the University of Chicago Press.

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PHOTOGRAPHY_AUTOFOCUS SYSTEMS

Focusing in a Flash

High-quality cameras all employ the same basic system for automatic focusing, known as phase-detection autofocus. In a single-lens reflex (SLR) camera, light from a part of the scene passes through the lens and then through the camera's reflex mirror, which is partially transparent. (The reflex mirror flips up when the shutter button is pressed to allow the image to fall on the film.) A submirror, attached to the back of the reflex mirror, directs the light that comes through the main mirror downward to the autofocus module.

After passing through various lenses and filters, the light rays fall on an array of light-sensitive charge-coupled devices (CCDs). It is the distance between the illuminated CCD elements that indicates how close the image is to being in focus. A logic circuit constantly monitors that separation and drives a motor that spins the focusing ring of the lens, shifting the focus. When the separation hits a predetermined value, the logic circuit stops the motor and flashes lights in the viewfinder to indicate that the image is focused.

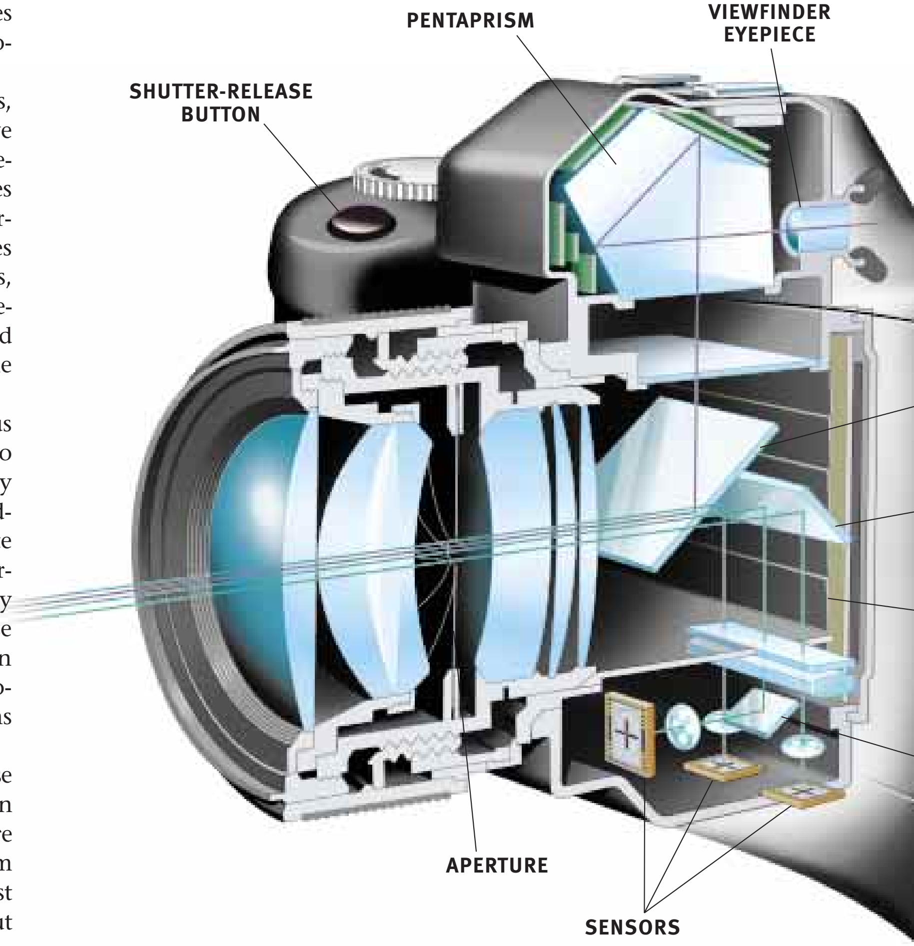
The basic scheme for phase-detection autofocus was the subject of patents awarded in the U.S. to Honeywell in the 1970s. Honeywell's technology was first used in the Konica C35 AF, a point-and-shoot camera that sold briskly but briefly in the late 1970s. In comparison with today's systems, this early implementation was slow and easily stymied by low light or low contrast. In the mid-1980s Japanese camera manufacturers, which had been working on autofocus systems for about 15 years, began introducing improved phase-detection autofocus systems in their models sold in the U.S.

Honeywell, in a landmark patent-infringement case noted for its nationalistic overtones at a time when fears of Japanese technological dominance were cresting in the U.S., sued Minolta over the Maxxum 7000 camera. Ultimately, in 1992, after Minolta lost the jury decision, the company had little choice but to pay Honeywell $127.5 million to license the autofocus system and a related low-light flash technology. Other Japanese camera makers were then forced to make similar deals with Honeywell.

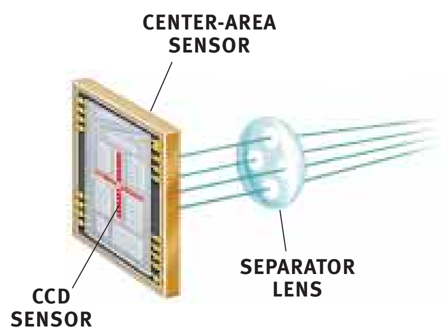
The relatively poor performance of early autofocus systems earned the technology a bad name among professional photographers, who resisted it for years. Great improvements in speed and reliability finally won over even that market segment, and today autofocus is a standard feature on 35-millimeter cameras ranging from modest point-and-shoot units to top-of-the-line professional models.

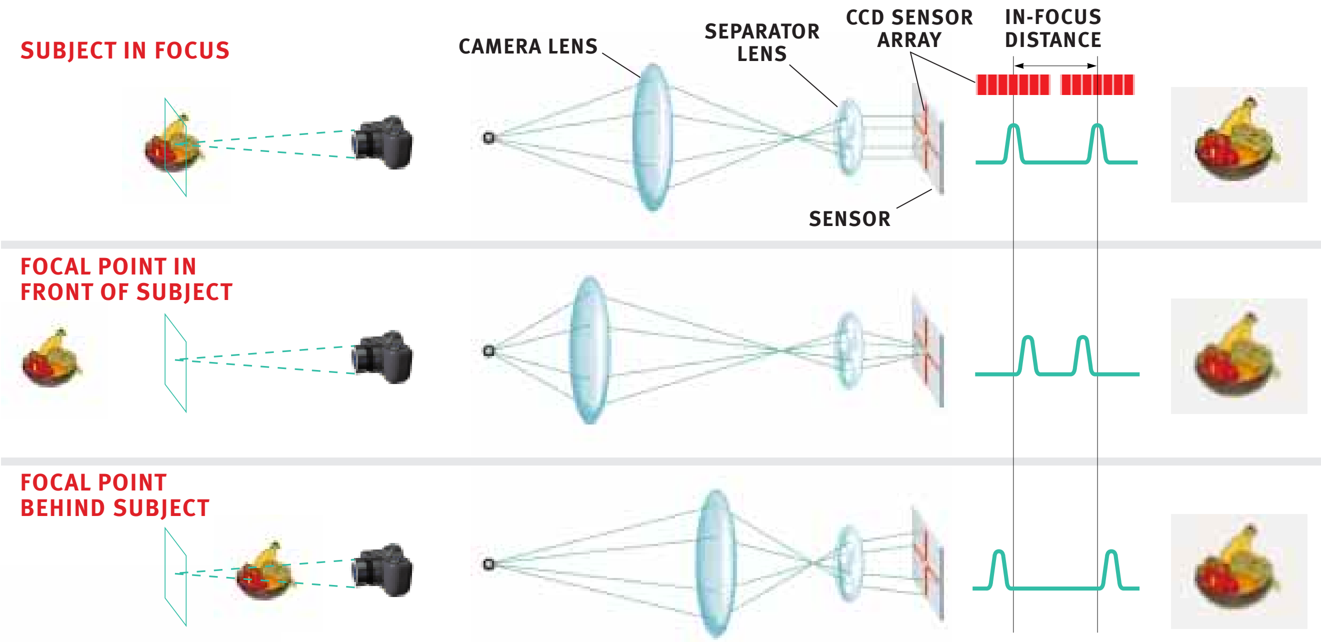
—Glenn Zorpette, staff writer

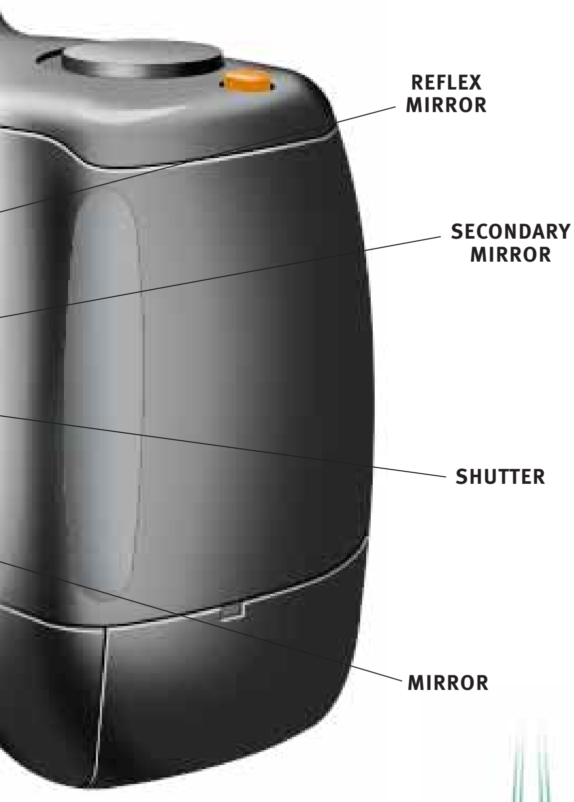
HIGH-END SLR cameras tie the autofocus to other functions. Most can take a light-meter reading of a "spot" area, just a few percent of the image. In these models, the autofocus can be coupled to the light meter, so that the unit focuses on the subject while simultaneously taking a spot-meter reading of it. Sophisticated software permits the system to pick out the probable subject. Flashing lights in the view screen indicate which of the several autofocus arrays is activated, revealing which object the camera is focusing on.



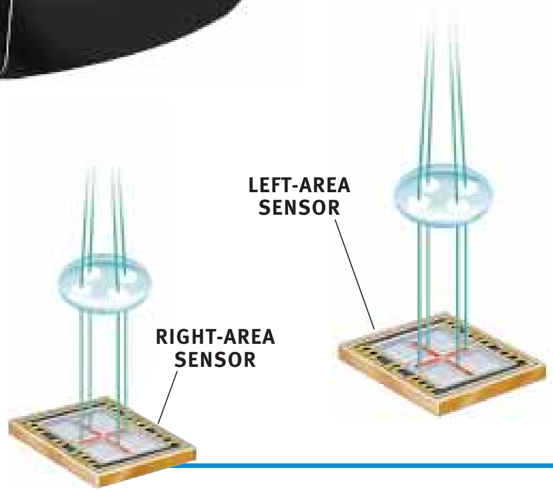
TYPICAL AUTOFOCUS MODULE includes several pairs of CCD sensor arrays, each with a corresponding set of separator lenses. The positions of the pairs of arrays enable the camera to focus on subjects in different parts of the viewfinder—right, left or center, for example. The separator lenses split the light beam coming from the subject, casting light on each half of the pair of sensor arrays.







OPTICAL LAYOUT shows how the camera determines where the focal plane is. Separator lenses create two identical images, each of which falls on half a pair of CCD sensor arrays. When these points of light are a set distance apart, the subject is in focus. When the separation is too small (*middle panel*), the focus is in front of the subject. When it is too large, the focus is behind the subject.



DID YOU KNOW ...

- In the early days of autofocus SLRs, the motor that spun the lens's focus ring was usually in the lens itself. Eventually, most manufacturers shifted the location of the motor to the camera body. The exception was Canon, whose autofocus lenses each have an internal motor for autofocusing. With the motor in the body, a better body can bring new features to an existing (and oftentimes costly) set of lenses. On the other hand, with the motor in the lens, the motor can be customized to accommodate the lens's particular size and weight, which can vary greatly among lenses of different focal lengths.

- High-end SLR cameras have a continuous autofocus feature that allows the user to take sharp pictures of a subject moving toward or away from the camera. When the shutter button is pressed halfway down, the autofocus system focuses on the moving object and begins tracking it. When the button is pushed all the way, the lens continues tracking the object right up to the moment the shutter actually opens, which can be a quarter of a second after the button is fully depressed.

- According to their manufacturers, the best modern autofocus systems can work in light levels down to an exposure value (EV) of –1, which corresponds to an amount of illumination that would require an exposure of four seconds and an aperture of 1.4 for a film speed of 100. Early systems could not work in light levels below an EV of about +4, which corresponds to an exposure of 1⁄8 second at the same aperture and film speed. At very low light levels, the better systems focus on a pattern of red light, projected briefly from the flash unit onto the subject.

ILLUSTRATIONS BY GEORGE RETSECK

AQUA_CULTURES

How to Rear a Plankton Menagerie

Shawn Carlson explains how to raise single-celled aquatic creatures—lots of them

The Monterey Bay Aquarium in California houses some of the finest marine exhibits in the world. So when the staff recently offered me a personal, behind-the-scenes tour, I couldn't refuse. Tim Cooke and Ed Seidel made the visit absolutely fascinating, and I am indebted to them for their hospitality. Tim, an aquarist extraordinaire, even let me in on a few secrets for raising plankton.

And he should know them: the Monterey Bay Aquarium grows a lot of plankton. Tim rears tons of the stuff each year to feed the thousands of voracious fish, crustaceans and jellies under its care. But these single-celled critters are not just fish food: they are quite intriguing in their own right and can provide amateur scientists with endless hours of delightful observation. When viewed under a microscope, the tiny phytoplankton (plants) and zooplankton (animals) are amazingly beautiful and complex.

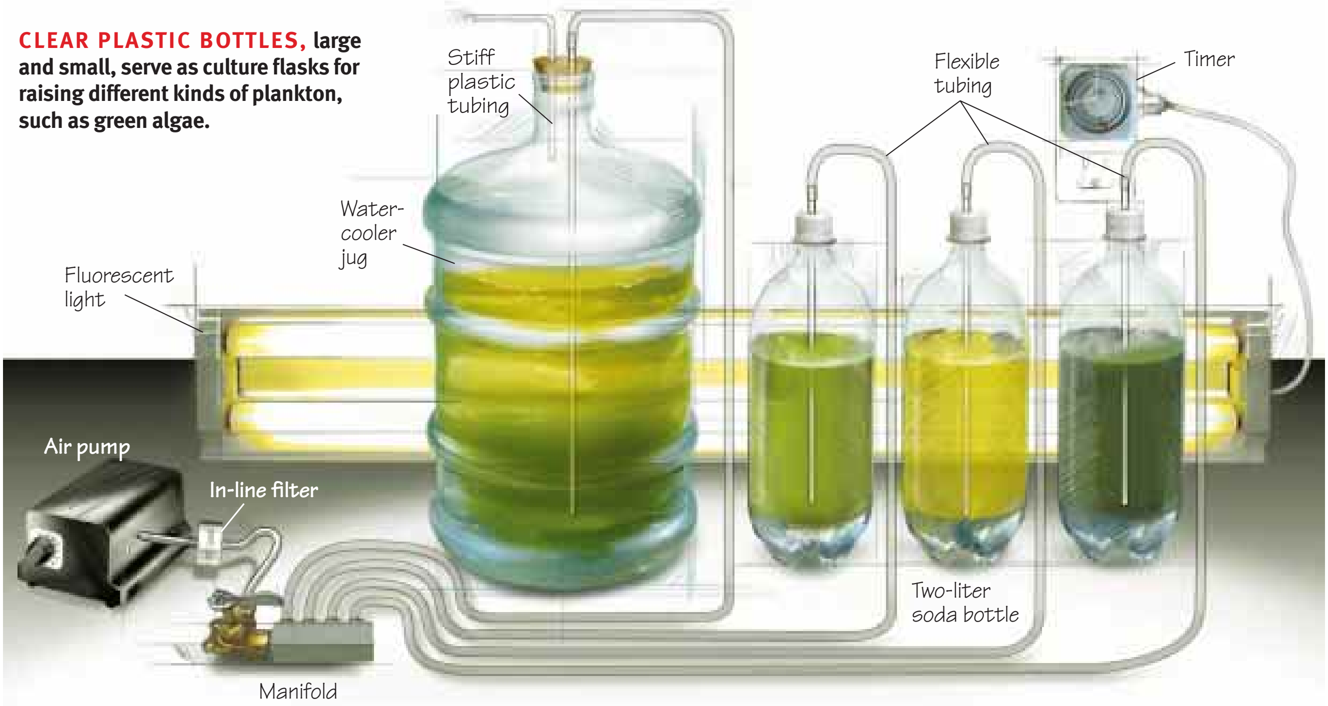
These creatures can also be useful for many kinds of research. For example, phytoplankton such as green algae are great for investigating the fundamental biochemistry of photosynthesis. And members of a zooplankton group called rotifers, which measure a mere 400 microns across, serve as the microscopic equivalent of a miner's canary, because they are sensitive to toxins and therefore may be used to monitor the health of estuaries and streams.

Amateurs can easily rear both marine and freshwater plankton for examination, for feeding larger aquatic animals or for use in more advanced research projects. Ocean enthusiasts should go to their local aquarium store and purchase a kit to make 50 gallons of seawater (for about $15) as well as a simple salinity tester. You'll need to order the plankton from Aquaculture Supply (www.aquaculture-supply.com or call 352-567-0226). Make sure they also sell you a copy of *Plankton Culture Manual,* by Frank H. Hoff and Terry W. Snell (Florida Aqua Farms, 1999; $26.50)—the bible of plankton cultivation. I recently grew up a batch of *Nannochloropsis* (catalogue no. AA-NCP, $8.50) and *Tetraselmis* (AA-TET, $11), both green algae that can live in either freshwater or salt water. And I raised a little saltwater rotifer known as *Brachionus plicatilis* (AB-R1S, $10). You may also want to grow diatoms—a type of algae that strengthens its cell walls with fantastically beautiful silica structures. If so, a good choice might be *Chaetoceros* (AA-CHA, $11).

Clear plastic soda bottles in the two-liter size make ideal culture flasks. To prevent yours from being taken over by bacteria, you'll need to sterilize everything before you begin. So go to a store that sells pool supplies and purchase granular chlorine. Dissolve as much of the solid as possible into 30 milliliters (about an ounce) of warm water. Then prepare a 10-to-1 dilution by mixing five milliliters (one teaspoon) of the concentrated chlorine solution into 45 milliliters of distilled water. Be careful you don't transfer any undissolved crystals into the sterilizing solution you are preparing.

Next, fill your two-liter containers nearly to the top with either distilled water or seawater and add five drops of the sterilizing solution to each. Wait two

CLEAR PLASTIC BOTTLES, large and small, serve as culture flasks for raising different kinds of plankton, such as green algae.



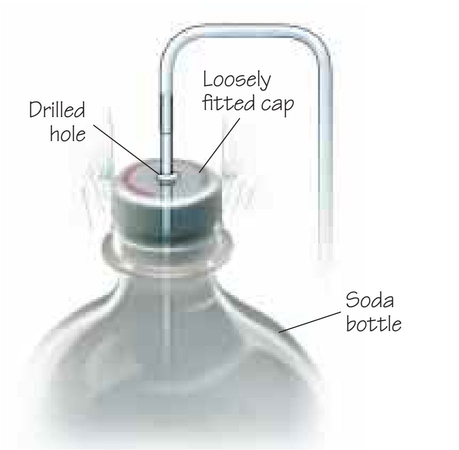
ALL ILLUSTRATIONS BY DANIELS & DANIELS

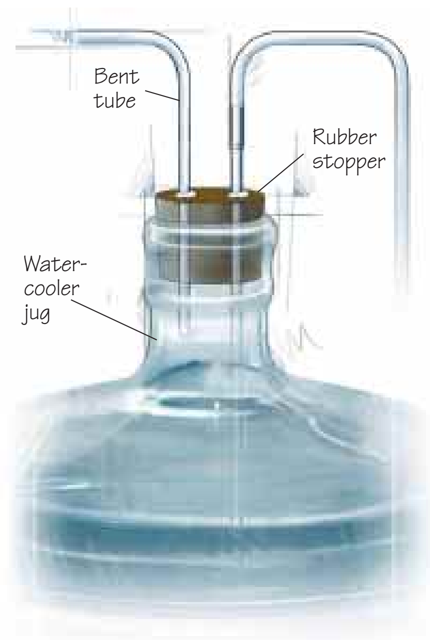
hours for the chlorine to do its work. Chlorine evaporates quickly from solution, so you'll have to make up a fresh batch of sterilizing fluid every time you need some. In this sense, evaporation is a nuisance, but you can take advantage of it to remove the chlorine in the flasks by bubbling air through the water for about 24 hours. A few drops of bottled dechlorinating agent from a tropical-fish store will do the job in seconds. Either way, don't introduce your plankton until you've verified, using a kit for testing home pools, that no chlorine is detectable.

A single pump for a 10-gallon aquarium can easily aerate 10 culture flasks. Use a multiport manifold (a common piece of aquarium plumbing with one input and many outputs) to distribute the air to the different cultures. Some stiff plastic tubing (also available at the aquarium store) will allow you to inject the air at the bottom of each flask. But you should pump it through a filter with 0.5-micron openings, such as SLFH05010 from Millipore ($79 for a 10-pack, www.millipore.com; 800-645-5476), to keep bacteria from invading your sterilized containers [*see illustration on opposite page*].

Now enrich each flask with the appropriate nutrients. Aquaculture Supply sells Micro Algae Grow (catalogue no. FA-MIS, $4.20) for cultivating most kinds of green algae and Liquid Silicate Solution (FA-SS6, $3.50) for culturing diatoms. Directions come with the packages.

The plankton samples arrive in the mail growing in small plastic dishes filled with gelatin. To remove the living cells, submerge the gel beneath a thin layer of your growing solution and allow it to soak for 12 hours. The microorganisms will then easily rub off the gel under the gentle pressure of a sterile cotton swab. Inoculate each flask with about 10 milliliters (two teaspoons) of the resulting solution. Make sure at every step that all your instruments are germ-free by carefully washing them with detergent and sterilizing solution and then rinsing them with distilled water.





LOOSELY FITTED CAP on the soda bottle (*above*) allows the escape of air injected through the central tube but does not let contaminants fall in. A rubber stopper with a bent tube set in one of its two holes (*right*) provides the same function on the watercooler jug.

Ideally, your culture should be incubated at 19 degrees Celsius (about 66 degrees Fahrenheit), but I had no problems just letting mine sit at room temperature. Avoid exposure to direct sunlight, because the sun's rays can quickly heat your flasks to lethal levels. Instead place the flasks in front of a bright fluorescent lamp for 18 hours a day. A standard bulb of at least 2,500 lumens works fine, but some aquarists recommend "grow-lights," which produce more of the energetic blue photons used in photosynthesis.

Once you start things going, you should keep aerating the water constantly. In about a week, your container should attain a deep green hue, which indicates that the culture is mature and ready to feed to other aquatic creatures. In as few as 10 days, the cellular population explosion can generate enough waste to poison itself, so don't wait too long. If you extract 10 milliliters of mature culture to start a new batch, you'll never need to purchase another starter gel.

The professionals grow larger quantities of algae in 20-liter (five-gallon) containers called carboys. Some scientific supply companies charge $100 for these transparent plastic bottles, but you could just as well use a discarded five-gallon jug from a watercooler. Aquarists usually install a special arrangement of tubing into their carboys to pass the air through without risking contamination. I used a hot-air gun to bend a stiff plastic aquarium tube and achieved the same result [*see illustration at left*].

Want to grow a lot of plankton? Fill an empty water jug with distilled water or salt water and add five milliliters of fresh sterilizing solution. As before, let things stand for two hours, then dechlorinate the water and test it. Add the necessary nutrients and inoculate the jug with the contents of one complete flask of mature culture. Connect the air pump and make sure the container gets plenty of fluorescent light.

You can track the rate of growth with a special dipstick sold by Aquaculture Supply (AC-DM9, $7.75). Just submerge the stick into the jug until the greenish water obscures the black ring on the bottom, then read the depth off the scale on the side. For each species, you can gauge the density of cells using a table supplied with the stick. After about a week, my water jug had more than 10 million cells living in each milliliter—some 200 billion cells in all.

With a stable supply of algae, even if it's only two liters' worth, you'll be able to raise rotifers. Although procedures for rearing these sophisticated aquatic predators are straightforward, they are more complex than the simple steps described here for raising their algal food. The interested amateur should consult Hoff and Snell's excellent book for pointers. And keep a lookout for future installments of this column describing amateur research projects that use plankton. SA

To get your feet wet, Aquaculture Supply sells three complete introductory algae-growing kits: the Maxi Culture Kit (GA-MACK, $77), the Mini Culture Kit (GA-MICK, $48) and the Algae Culture Kit (GA-ACK, $41). Each kit includes Hoff and Snell's manual. As a service, the Society for Amateur Scientists can provide an air filter and a carboy-size stopper for $20. For more information, consult the society's Web site, www.sas.org, and click on "Forum." You may write the society at 4735 Clairemont Square PMB 179, San Diego, CA 92117, or call 619-239-8807.

LOGIC_QUASI-FRACTALS

A Fractal Guide to Tic-Tac-Toe

Ian Stewart finds a familiar shape in unexpected places

I am being haunted by a fractal. In a recent column [see "Sierpinski's Ubiquitous Gasket," August 1999] I described several occurrences of the fractal known as Sierpinski's gasket, which can be obtained from a triangle by successively deleting an inverted triangle half its size. Ever since, readers have been alerting me to new sightings of this versatile figure. Its latest incarnation is in the field of mathematical logic. Patrick Grim and Paul St. Denis of the State University of New York at Stony Brook sent me a paper entitled "Fractal Images of Formal Systems" (Journal of Philosophical Logic, Vol. 26, No. 2, pages 181–222; 1997).

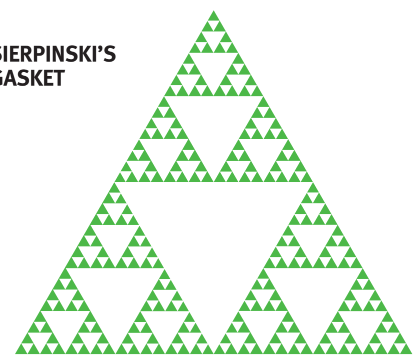
A fractal is a shape that can be divided into parts that are smaller versions of the whole. A genuine fractal such as Sierpinski's gasket has detailed structure on all scales of magnification: any piece of it, no matter how small, will resemble the whole. A quasi-fractal, in contrast, is an approximation of a true fractal—it has detailed structure over a large but finite range of magnification scales. The patterns of a quasi-fractal do not continue to infinitely fine scales, but because the human eye cannot distinguish such small details, quasi-fractals look convincingly fractal. One of the accomplishments of Grim and St. Denis was to devise a quasi-fractal diagram that represents all the possible games of tic-tac-toe.

As everyone knows, tic-tac-toe is played on a 3-by-3 grid of squares by two players, X and O. Each player takes turns marking squares, and the first to get three in a row (across, down or diagonally) wins. Traditionally, X goes first, and optimal play always results in a draw. But exactly how many games are possible? At X's first turn, he chooses among nine squares; then O chooses among eight, and so on. So the total number of games is $9! = 9 \times 8 \times 7 \times 6 \times 5 \times 4 \times 3 \times 2 \times 1 = 362,880$.

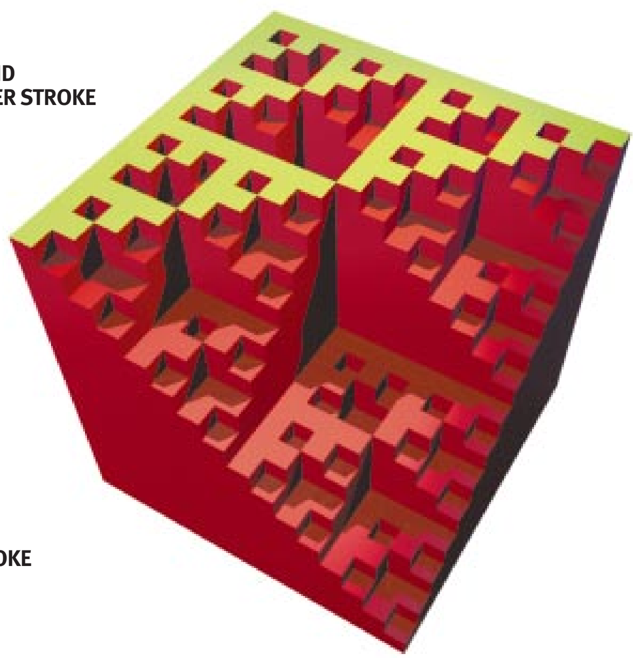
Here's how Grim and St. Denis built their quasi-fractal. Start with a big 3-by-3 square grid, and divide each square into a 3-by-3 subgrid [see illustration on opposite page]. Player X has nine opening moves, corresponding to the positions in the larger grid. One possible move is that X chooses to mark the top left corner. Find the 3-by-3 subgrid in the top left corner of the big grid and draw an X in the subgrid's top left corner. The subgrid is now a picture of the game after this opening move. Another possibility is that X opens with the bottom center square; to represent this move, find the subgrid in the bottom center square of the big grid and draw an X in the subgrid's bottom center square. In this way, each of the nine subgrids receives an X in a different subsquare.

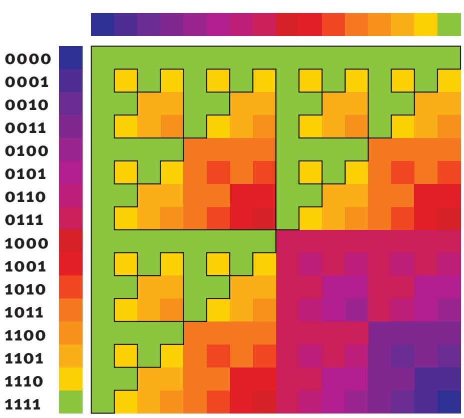
Now concentrate on the subgrid in the top left corner of the big grid. X's first move is already drawn in the top left corner; the other eight subsquares represent

SIERPINSKI'S GASKET



VALUE SOLID FOR SHEFFER STROKE

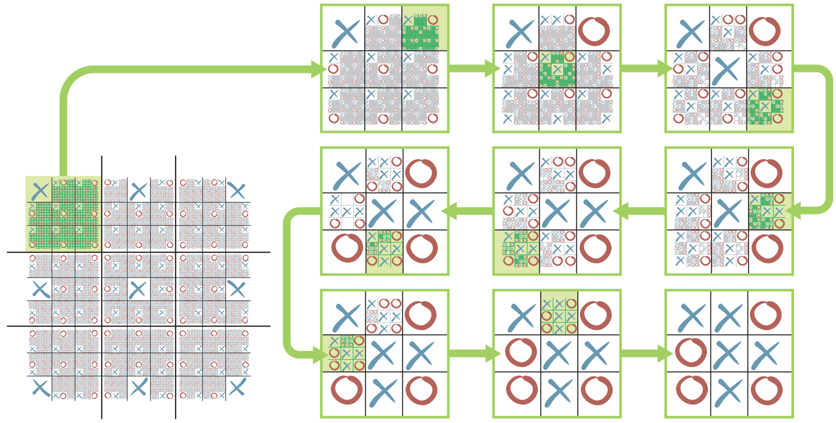




COLOR DIAGRAM FOR SHEFFER STROKE

SIERPINSKI'S GASKET (*above left*) can be approximated using mathematical logic. Plugging four-digit binary numbers into the truth table for the Sheffer stroke yields a color diagram in which the green squares form a gasketlike shape (*left*). The figure can also be seen in the value solid for the Sheffer stroke (*above*).

ALL ILLUSTRATIONS BY BRYAN CHRISTIE



ALL POSSIBLE GAMES of tic-tac-toe can be depicted in a quasi-fractal diagram. The squares in the 3-by-3 grid are divided into smaller grids that show all the opening moves (*right*). Subsequent moves are illustrated in still smaller grids created by subdividing the unoccupied squares. A sample game can be viewed by repeatedly magnifying sections of the diagram (*far right*).

possible moves for O. If we just put O's in each of those subsquares, though, we would have nowhere to put X's second move. Instead we repeat the trick already used for the opening move: We divide each of the eight unmarked subsquares into a 3-by-3 grid of sub-subsquares, getting eight small tic-tac-toe boards. We put an X in the top left corner of each, to represent X's opening move. Then we put one of O's eight possible moves into each of the small tic-tac-toe boards.

We can continue in this fashion, recording all the possible moves in subgrids of ever smaller size. At every stage, all the unoccupied squares are subdivided into 3-by-3 grids, and all moves previous to that stage are copied into the cells of those grids. The final figure has a quasi-fractal structure because the rules of the game are recursive: the possible moves at each stage are determined by the moves made before. The geometry of fractals is also recursive: similar shapes repeat on ever smaller scales. The tic-tac-toe figure is a quasi-fractal rather than a true fractal because the game ends after a finite number of moves.

Now we turn to logic. The simplest area of conventional mathematical logic, propositional calculus, is concerned with statements whose "truth-value" is either 1, representing true, or 0, representing false. For example, the statement P = "pigs can fly" has a truth-value of 0, whereas Q = "Africa is a continent" has a truth-value of 1. Statements can be combined using various logical operators, such as AND and OR. If P and Q are as above, the statement P AND Q is "pigs can fly, and Africa is a continent." This statement is false, so the truth-value of P AND Q is 0. The results of applying AND to statements can be summed up in a truth table:

P	Q	P AND Q
0	0	0
0	1	0
1	0	0
1	1	1

It is also possible to change 0 to 1 and 1 to 0 by applying the operator NOT: that is, NOT P is true if P is false, and vice versa.

There are 16 possible truth tables for

two statements, representing all the possible ways to put 0's and 1's in the table's final column. We can denote them with successive four-digit binary numbers: 0000, 0001, 0010, 0011 and so on, up to 1111. (In decimal notation, these numbers are 0, 1, 2, 3, ... , 15.) This list leads to another quasi-fractal. To draw it, sketch a 16-by-16 array of squares and add a border above the top row that identifies each column with one of the binary numbers [see illustration on page 86]. Then add a similar border down the left side of the array to enumerate the rows. Choose 16 different colors to correspond to the 16 binary numbers and color the border squares accordingly. Next, choose a logical operator: for example, the Sheffer stroke, which is represented by the symbol |. In computer engineering, the Sheffer stroke is known as NAND, because P | Q = NOT (P AND Q). Its truth table is:

P	Q	P | Q
0	0	1
0	1	1
1	0	1
1	1	0

Now, for each of the squares in the 16-by-16 array, put the square's four-digit row number in the first column of the P | Q truth table and put the square's column number in the table's second column. Then perform the NAND operations and put the resulting truth-values in the table's final column. This yields another four-digit binary number. Find the color that corresponds to this number and use it to mark the square in the 16-by-16 array. For instance, consider the square in row 5, column 11. In binary notation, these numbers are 0101 and 1011. Plugging them into the truth table for P | Q yields:

P	Q	P | Q
0	1	1
1	0	1
0	1	1
1	1	0

The number in the final column is 1110, or 14 in decimal notation. So the square in row 5, column 11 is given the color corresponding to 14.

The final product of this laborious process is shown in the illustration on page 86. Notice that the green squares, corresponding to the binary number 1111, form a shape very similar to Sierpinski's gasket! Instead of color-coding the picture, one can also graph the value of each square in a third dimension, as a height given by its decimal number divided by 16. For example, the height of the square in row 5, column 11 would be 14/16 = 0.875. These graphs are called value solids. In the value solid for the Sheffer stroke, a gasketlike shape can clearly be seen. The explanation is simple: any formal logical system that involves recursion—whether a game or a truth table—can provide a recipe for drawing quasi-fractals. SA

READER_FEEDBACK

In response to "Counting the Cattle of the Sun" [April], Chris Rorres of Drexel University tells me that more information can be found in a preprint entitled "A Simple Solution to Archimedes' Cattle Problem," by A. Nygrén of the University of Oulu in Finland. The preprint describes an algorithm for solving the problem that takes only five seconds to run on a Pentium II personal computer using Maple or Mathematica software. Links to electronic files of this preprint are on Rorres's Web page (www.mcs.drexel.edu/~crorres/Archimedes/Cattle/Solution2.html). *—I.S.*

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Books

REVIEW_IN PICTURES

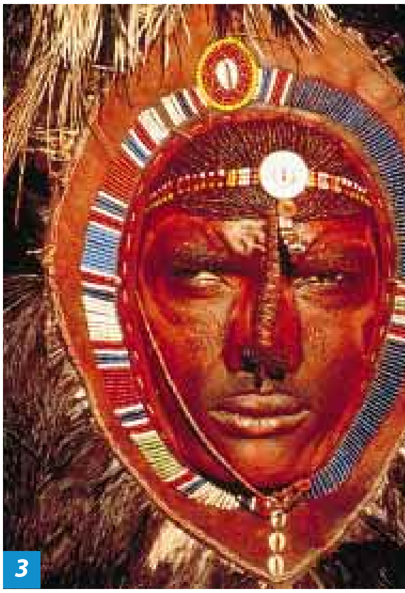
Hidden World

Two intrepid photographers explore the disappearing rituals of Africa

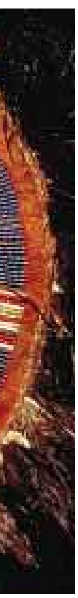
African Ceremonies
by Carol Beckwith and Angela Fisher
Abrams, New York, 1999
Two volumes, slipcased, $150

Carol Beckwith and Angela Fisher spent the past 10 years living and traveling in 26 African countries, gathering material for this monumental two-volume set. They photographed 43 ceremonies that span the human life cycle—from birth, through initiation, courtship, marriage, royal coronations, seasonal rituals and healing exorcisms, to death. By living among the people, learning their languages, eating their foods and adapting to their pace of life, the women were able to witness ceremonies that might never have been recorded. Many of the traditions chronicled in *African Ceremonies* will disappear with the next generation.

Organized into sections corresponding to the cycle of life are nearly 850 full-color photographs. Some are an imposing 14 by 20 inches; all are stunning. Beckwith and Fisher introduce each section with a concise, informative essay. But it is the pictures that do the talking. —*The Editors*



1 Wodaabe competition of male charm and personality, Niger; 2 Surma girls decorate their faces to demonstrate friendship, Ethiopia; 3 Maasai youth becomes a warrior, Kenya/Tanzania; 4 Grandmother dresses her granddaughter for Ndebele wedding, South Africa; 5 Himba healing ceremony for women possessed by the spirit of a lion, Namibia



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5

Laws of Calorie Counting

What is the bottom line on the energy we take in? **Philip & Phylis Morrison** recount the heroic, decade-long effort to find out

Gazing into our quiet street, we see a scrap of paper ruffle in the breeze or a little water creep along the gutter. Those motions have clear causes: wind and gravity. But the local raccoon that hunts by night and the car that rolls past are distinct. The forces that impel both are mustered internally: timed muscular contractions lift and plant paws, and a stream of explosions turns the wheels. Each self-mover draws on a diet of energy, the one scraps of food, the other gasoline.

The quantity of energy we take daily from food has entered common parlance in the U.S. Every edible offering on the shelf declares by law its nutritional energy in calories—units of heat, a form of energy release easily measured. (Bottled water declares itself out of the energy game: 0 calories per serving.) One kilocalorie is heat enough to raise the temperature of one kilogram of water by one degree Celsius. (Many labels carry the term "calorie" but all the same intend by it the kilocalorie.) The energy we expend is neither provided as nor mainly used as heat.

By the mid-19th century, physicists and physiologists were on the track of energy balance in living creatures. In steady state, all energy expended has to be strictly accounted for by net energy taken in. The chemists made it clear that the foodstuffs we digest react through many steps with airborne oxygen, to produce the products of biochemical "combustion" without any frank fire. Our body is warm but nowhere near fiery. More a fuel cell than a heat engine, it absorbs oxygen to release chemical energy, turning energy-rich constituents of the diet into stabler compounds eliminated as wastes, including the invisible, incombustible gas carbon dioxide, exhaled with each breath.

Our vital co-food is atmospheric oxygen, produced mainly as gaseous waste by green plants benignly indifferent to its market value for life's fire and for the sparks of hearth and engine. We ingest mainly plant carbohydrates, the stoutest staff of life, and the plants take carbon dioxide from the air. The rate of change—whether swift flame or slow metabolism—does not affect the energy yielded in passing from one well-defined chemical state to another, all products taken into account.

The first experimental checks of energy balance in animals were made by two men trained in the lab of a celebrated Munich physiologist. Young Max Rubner measured in 1894 the heat output of dogs; that heat balanced the measured heat of combustion of their food, corrected by adding the few percent released on oxidizing the urine and feces. The dogs' sporadic mechanical work was ignored.

One college athlete expended 10,000 kilocalories cycling in place for 16 hours.

The second was a mature American chemist, Wilbur Olin Atwater. He came home to the U.S. in 1892 to inspire, instrument and direct an ambitious decade-long experimental campaign that asked whether human metabolism was tightly bound by the law of energy conservation.

Atwater and his group worked in the secluded basement of the science hall at Wesleyan University in Middletown, Conn. By 1905 they had laid the quantitative foundations of the present calorie-counting and labeling activity around foods, with results used to this day the world over. Whether you count calories or not, you firmly follow Atwater's laws, of course subsumed under the general law of energy conservation.

Atwater and his physicist faculty colleague E. B. Rosa completed the first notable human calorimeter in 1894. A photograph shows their calorimeter: a small sealed room, four by seven feet in area, with a low ceiling. It was furnished with a folding wall bed, a folding chair, a telephone, a triple-glazed window that also provided entry, and a stationary bicycle, often used to extract work, released as heat, from the subject. Double walls of sheet metal enclosed the room, and three wooden walls outside that metal box guided layers of air under control. The copper inner wall held two grids: one of cooling-water tubes, and another of electrical heating coils. A large copper-wire resistance thermometer measured the room's air temperature to a hundredth of a degree; a second one kept good thermal contact with the copper wall. The ruling art here was to maintain a single room at air temperature and surround the human heat source by material at nearly matching temperature, all unmonitored gain or loss kept effectively nil. Water pumped through the walls of the room left warmer than it had entered: that change measured the energy provided by the test subject.

Mirror galvanometers were the instruments of that world—DC, analog, sensitive—and patiently read out by hand. Two shifts of eight persons each recorded the temperatures, controlled the air and water flows, weighed food and water, caught the subject's water vapor by chilling, and calculated it all. The system was calibrated by weighing the fuel used by a lamp that burned pure alcohol. Many special digestion runs were made, to get the heat content of

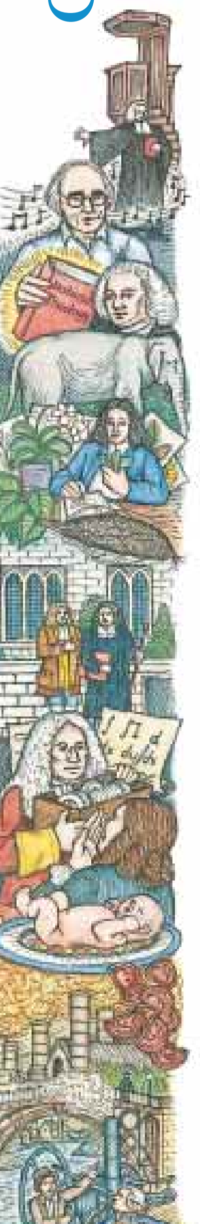
Continued on page 95

DUSAN PETRICIC

The Grand Plan

In which **James Burke** connects the dots between theology, calculus, social satire, locomotives, Napoleon and economics

DAVE PAGE



Whenever I begin to feel that my life is one of trivia and secondary sources, I whistle a happy tune and recall the words of Reverend William Paley (1743–1805), a well-heeled English prelate who managed almost never to preach at the many ecclesiastical livings he almost never visited. And on the rare occasion when he did climb into the pulpit, he operated by the precept "Write one sermon and steal five."

Paley was the guy whose 1802 "Natural Theology" (a last, fixity-of-species Grand Plan fling before Darwin) bolstered religion by showing how a rational examination of design in nature proved the existence of God during a period when scientific and technological change were calling all in doubt. An elephant's "unbending" neck, for example, was compensated for by its flexible trunk. All the different bits of nature were there for a specific purpose, and the entire thing worked together for a common end.

In keeping with "write one, steal five," the metaphor by which Paley's work is best remembered—"God the watchmaker"—wasn't his. Nor was the whole basic idea, because he probably got it from something written over 100 years earlier: "The Wisdom of God," which treated much the same topic, with much the same purpose.

Its author, John Ray (another cleric-turned-naturalist), also lived at a time when epistemological rugs were being pulled out from under. For Ray, it was the avalanche of new species coming in from explorations East and West. He decided to start classifying the confusion and became an early eco-tourist, traveling throughout Britain and the Continent, peering and scribbling. If it came out of the ground, he described it, in a multivolume tome (*History of Plants*) that finally contained 10,000 new entries. Really magnum opus. Unfortunately, Ray was to be overshadowed by the juggernaut success of the naming-of-parts classifier for all seasons: Linnaeus. Who named a yam after Ray. Gee, thanks.

Ray's contemporary in math and Greek (a popular mix) at Cambridge was another overshadowee (well, have you ever heard of Isaac Barrow?). The great Swiss noodler Jakob Bernoulli argued not long after Barrow's death that Barrow's work anticipated the calculus of Newton (historians still argue over whether Barrow was a teacher of, or an influence on, or one of the "five sermons" of, the Great Gravitator). Whether or not Barrow inspired Newton, it is undeniable that very few people could read and understand Barrow's stuff except Newton.

And the man who beat Newton to calculus (or didn't, as historians still argue) was Gottfried Leibniz, whose immense talents are still waiting to be fully recognized in most classrooms. One of Leibniz's many ideas was to develop an alphabet for reasoning, in which grammar and vocabulary became symbols, to be manipulated innovatively in a machine, a wooden prototype of which he demoed in London in 1673. Lead-balloon time all around, to judge by the "looney idea" treatment it got in one of jogger and mega-satirist Jonathan Swift's pieces.

Mind you, Swift slagged off anybody at the drop of a hat, which might be why he never got anywhere, career-wise. Typically, he raised British government hackles when he drew attention to starvation and high birth rates in Ireland by suggesting that the solution to the problem was to add babies to the menu. Another Irish scandal that drew Swift's ire was known as "Wood's half-pence." In 1721 King George's mistress, Ehrengarde Melusina von der Schulenburg, a lady known for greed but not beauty, fiddled William Wood (in return for a humongous cash backhander) the license to issue new Irish coinage. Wood then skimmed a little profit by shortchanging the amount of copper in the coins. And all this he did without a word to the Irish, who went ape (as did Swift). Wood lost his license

Swift suggested that the solution to the population problem was to add babies to the menu.

(and the one he had for new American coins).

Wood's foundry smelted with coal coked clean of impurities, an idea from the eminent ironmaster Abraham Darby, who realized what the steam engine was going to do to the metal market and so built a high-tech ironworks at Coalbrookdale, on the river Severn. Did so well, his family was still doing it to the third generation. In 1802 Abraham III's works built the first high-pressure locomotive, designed by Richard Trevithick, for use in hauling ore out of mines.

Trevithick was a larger-than-life Cornishman: inventor, entrepreneur, pals with the great. He spent 10 years engineering in South America, came home penniless, died in debt. His career had started after a meeting in London about his locomotive with an ex-schoolmaster from Rumford, N.H.—Ben Thompson, who'd fought for the Brits during the War of Independence and therefore left for England. There he founded the Royal Institution, became Sir Benjamin, and then (for services in Germany) Count von Rumford.

PATRICIA J. WYNNE

Thompson was another inventor with a practical bent, who came up with nifty ideas on fuel and fireplaces, to keep people warmer. Ended up hot stuff on heat. About which he won a blazing row ("Heat is result of motion") with French scientist Claude-Louis Berthollet ("No, it isn't"). Berthollet was by this time a chemical biggie. Not only was he the guy who first realized that chemical reaction was related to mass, and discovered that chlorine would bleach, and worked with all the stars (Lavoisier, Monge, Gay Lussac et al.), and was commissioner of agriculture and an educational reformer and member of the Academie Française and professor, and got the Légion d'Honneur—Napoleon loved him enough to take him on the French occupation of Egypt. He also sent him to vanquished Italy to choose which Great Italian Art to snitch. By 1804 Berthollet was running the French mint.

One of Berthollet's less illustrious fellow bureaucrats was an unknown named Laminière. All else I can find on this person was that in 1815 his daughter, Adèle, became the first wife of the son of the chief justice of Newfoundland, one Randolph Isham Routh, who had been the senior British commissariat officer at Waterloo when things went nasty for Napoleon. After Adèle's unfortunate early death, Routh married the cousin of the chief justice of Canada (was Routh a courtroom groupie?), and they had a son, Edward. Who ended up lecturer at Peterhouse, Cambridge, did dynamic stuff on dynamics and has to have been the greatest math teacher ever. Between 1862 and 1888 an unbroken line of 22 of his pupils won the top annual math prize. In 1865 the winner was John William Strutt, who would go on to become Lord Rayleigh and a very big cheese: Privy Council, Royal Society, Rumford medal, chancellor of Cambridge, Nobel for isolating argon, and a lot besides.

And the reason he's in this modest connective tale is because the same year he came out first in math, the man who got second banana was Alfred Marshall. Who probably means more than even Rayleigh to many readers of this column, because in 1890 he delivered what has been described as the finest economics treatise of his generation: *Principles of Economics*. A work that helped to shape economics in the 20th century: a Grand Plan, if you like, of how it all worked.

But not quite as Grand as the Plan by his wife's great-grandfather: William Paley. SA

Wonders, *continued from page 93*

weighed excreta. A variety of diets provided values for the energy efficiency of digestion for the main nutrients. The standard diet fueled the subject with canned, boiled, fat-trimmed beef, bread and butter, and milk and gingersnaps! The experimenters persuade us by their comprehensive design and meticulous care that the small error they finally reported—about 0.2 percent difference between input heat and measured work and heat output—is credible. Their results were soon published.

Today's nutritionists use the net energy yield in kilocalories per gram for protein, fat and carbohydrate content; the values found at Middletown, internationally adopted since 1947, are improved only in some details. The device widely used to measure food energy directly is a small, strongly sealed steel "bomb calorimeter," held in a stirred water bath. Within it, small dried samples of foodstuff are ignited in pure oxygen. (We used one as a "jelly doughnut bomb.") The long lists of popular foods rely mainly on a computation of energy yield from the reported recipes. They use net yield factors that trace back to Atwater. The measurement of human energy use has come into medical diagnostics, chiefly by proxy; equivalent oxygen consumption is measured rather than heat transfer. Human calorimeters are not commonplace; they have a limited but proud history over the century, in particular around the development of practical space suits for astronauts and cosmonauts alike.

Let us recall young J. C. Ware, college athlete and bicycle racer. That fit specimen was the leading resident of the Atwater calorimeter. Once Mr. Ware expended 10,000 kilocalories—12 square meals' worth—cycling in place for one 16-hour day, outworking the amazing road racers of the Tour de France. "Such subjects are to be cherished," writes Paul Webb, author of *Human Calorimeters* (Praeger, 1985), a fascinating history. (The various nutrition handbooks of the U.S. Department of Agriculture update the art. The Web is lively with today's microcalorimeters, widespread in the chemical and pharmaceutical industries.)

It was no small feat to set the inner fire of human life so convincingly among all fires, as once old Copernicus showed our earthly home to be but one among the visibly circling planets. SA

WOLFGANG BRADNER *JPL/IPAC*, EVA K. GREBEL *University of Washington*, YOU-HUA CHU *University of Illinois* AND NASA; KEITH KASNOT (*illustration*)

DAN WAGNER

Measure for Measure

Steve Mirsky offers a brief homage to the grams, liters, inches and hours that make it possible to keep track of our lives to at least some degree

"Don't forget your units, your joules!" my freshman chemistry professor used to say before every exam. Actually, he had a charming accent that made the admonition sound more like, "Dohn forgeh joor junits, joor hools," which at least partly explains why the words still ring in my ears more than two decades later. He thus reminded us students of the smelly science that without units—such as the joule, a standard quantity of energy—our test answers were meaningless. It was a good lesson. After all, 0.0648 gram of sodium chloride equals the proverbial grain of salt, a grain being an avoirdupois unit in good standing, also equal to 0.002285 ounce. But what are 10 or 20 of salt, other than an extra credit question on a philosophy exam?

Units are everywhere, with the exception of the previous sentence. We're drenched with ounces, laden with pounds, bursting with inches, overrun with feet. More obscure units include the hogshead, equal to 63 gallons for some reason. Speaking of hogsheads, there is the joke unit the milliHelen, which is the precise amount of beauty required to launch a single ship. There are profound, poetic units: T. S. Eliot's creation Prufrock notes, "I have measured out my life with coffee spoons." And this was way before Starbucks colonized the planet.

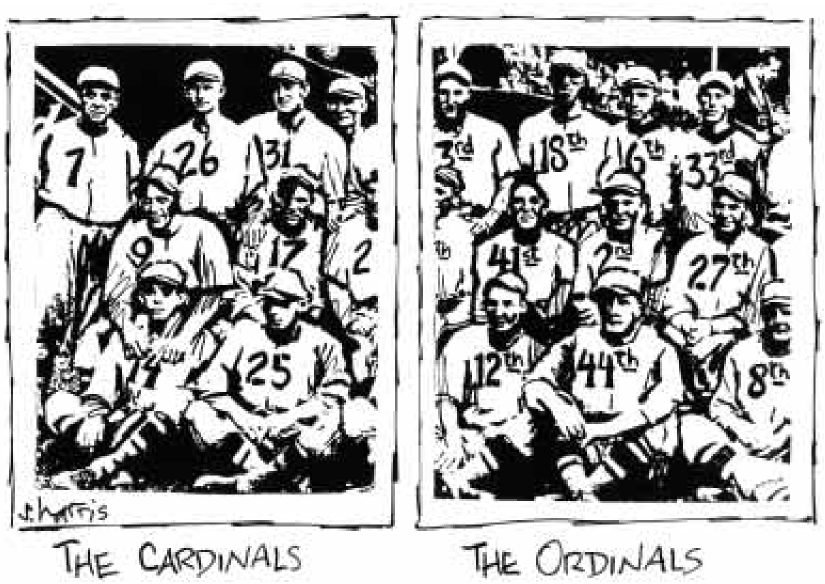
Units are indispensable to the most mundane activities—you can't buy a quart of milk without 'em. Most of the time, however, we focus more on the thing we are measuring and not on the units by which the thing gets measured. Units thus resemble sports officials: the only time you really pay any attention to them is when something stupid happens. Bring home a pint of milk instead of the requested half-gallon, and suddenly units become the topic of conversation. Mix up the force units of pounds and newtons in calculations, and suddenly your spiffy little $125-million Mars Climate Orbiter gets lost in space.

The Mars mess-up was major. The correction of a minor units blooper recently occurred in the *New England Journal of Medicine*. First we go back to last December, when the *Journal* published a letter detailing a study that measured the number of calories expended during a favorite American activity, gum chewing. The authors needed units to keep track of their subjects' gum-chews, a word that would have sounded to my chemistry professor like Raymond Chandler describing a detective. So for chews, they chose a time-honored unit for measuring regular, periodic phenomena: the hertz (Hz). Defined as the number of cycles per second, the hertz is actually quite familiar: your AM radio dial numbers are in kilohertz, and the FM side is in megahertz.

> After all, 0.0648 gram of sodium chloride is equal to the proverbial grain of salt.

The gum investigators blew it, however, when they noted that "the subjects were . . . instructed to chew at a frequency of precisely 100 Hz (a value that approximates chewing frequency at our institution)." Taken at face value, that meant that at their institution, the prestigious Mayo Clinic, gum chewers were ripping through the Bazooka at 100 chews per second. Oh, the humanity.

The error was caught by an observant reader whose letter was published in the *Journal*'s May 18 issue. The writer realized that the researchers really meant to say their subjects chewed 100 times per minute. Which once again brings to mind Prufrock, who mused about cycles per minute: "In a minute there is time for decisions and revisions which a minute will reverse." Which brings us back to the letter, whose author is well acquainted with decisions and reversals, being not a physician but an attorney. Which leads to one last thought: lawyers who read the *New England Journal of Medicine* probably make doctors tremble in a frequency range easily expressed in hertz. SA



SIDNEY HARRIS