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july 2001

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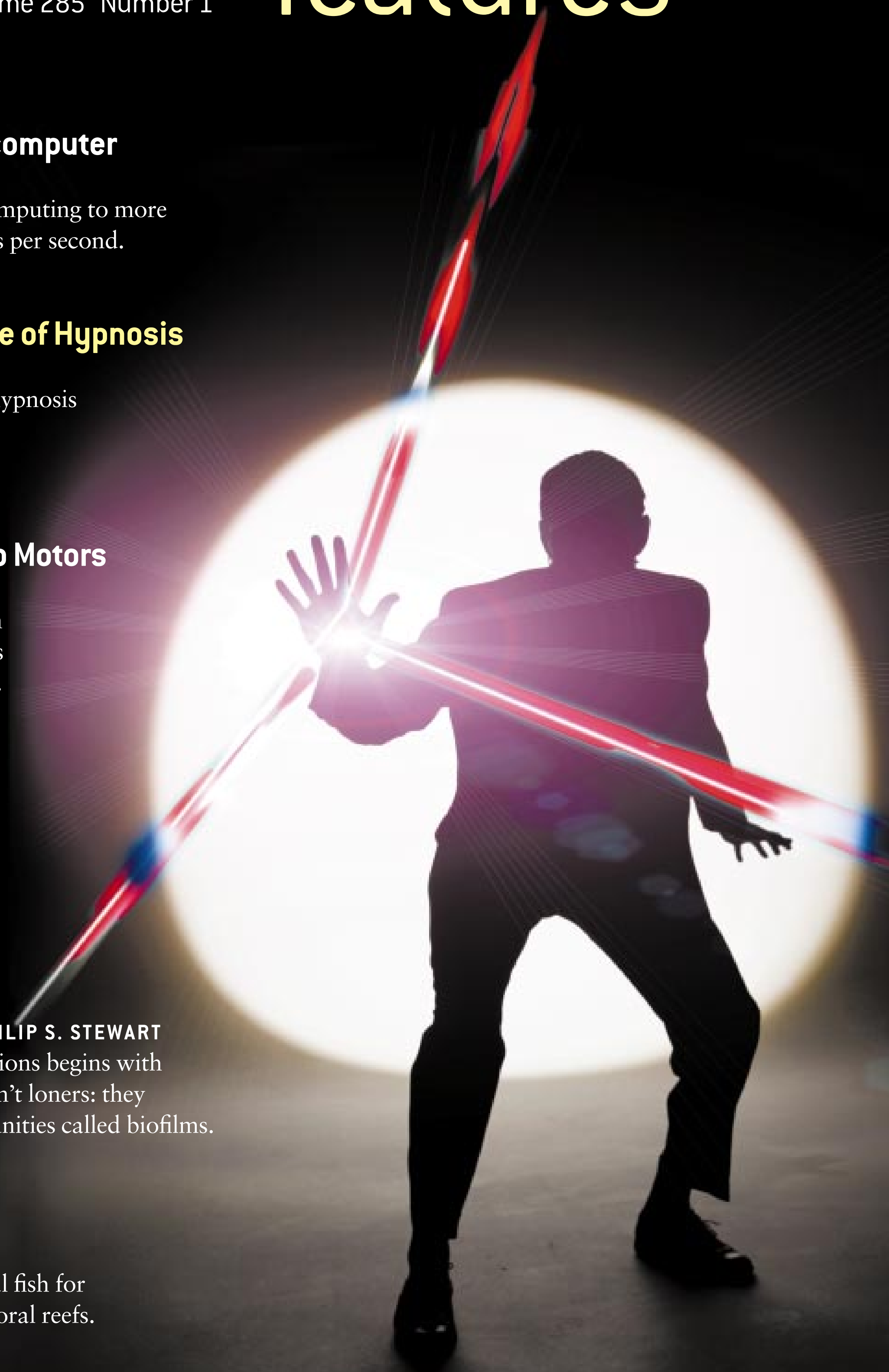

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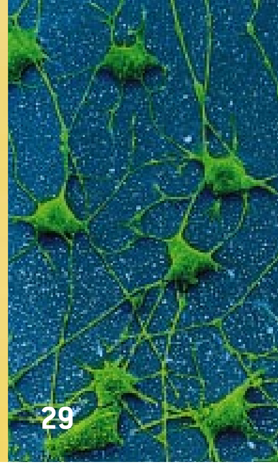


columns

Cover photographs: Beth Phillips (*watch*) and VCG/FPG (*watch chain*); preceding page: Chip Simons; this page, clockwise from top left: Eve Townson, FPG; Quest/SPL/Photo Researchers, Inc.; John McFaul

SA Perspectives

Air Traffic Out of Control

NASA recently flight-tested an advanced jet engine able to reach seven times the speed of sound. Talk was heard of hypersonic airliners zooming from New York City to Los Angeles in 45 minutes. If such a flight were made today, however, chances are good that the plane would be forced to circle over LAX for a few hours before it could be cleared to land.

As the numbers of airline passengers and flights increase, the nation's air traffic control (ATC) system is being stretched beyond its limits. With one in four flights expected to be late to the gate this summer, flying has become one of the more consistently annoying aspects of modern American life. Estimates indicate that delays cost airlines and air travelers some $5 billion in lost productivity every year. Along with inadequate runway capacity and the overscheduling of flights, the ATC system is a major culprit in this woeful display. And it's only going to get worse as today's U.S. flying public grows from 670 million a year to more than a billion within a decade.

The Federal Aviation Administration's abortive attempt to modernize the network of radars and computers that tracks air traffic, an initiative that dates back to the early 1980s, has become one of the worst debacles in the history of information technology. The original $12-billion project to install automation equipment, scheduled for completion by 1991, never met its targets, while wasting $2.8 billion in the process. As a result, current ATC computer technology is still horribly out-of-date.

During the Clinton administration, proposals to remove the operation of the system from the bureaucratic hands of the FAA and run it as a business got nowhere. Now growing air gridlock has returned the issue to center stage—and the Bush administration is giving commercialization a closer look.

This time, however, the debate is conditioned by the experience gained from commercialization programs beyond U.S. airspace. Nearly 20 nations have spun off their ATC systems into nonprofit or self-supporting government corporations. Key to these efforts is to let the new entity serve as traffic cop while the government maintains safety. Operations are supported by user fees similar to those paid today by airlines and general aviation pilots. One oft-cited model is Canada. There a nonprofit company, Nav Canada, has managed to cut delays and expenses even as it upgraded technology. It is run by a stakeholder board of aviation interest groups that has structured fees to better balance user demand with airport capacity.

ATC commercialization could permit the faster implementation of free-flight technology, which would let planes fly more direct routes. Currently aircraft are funneled into single-lane highways in the sky. One way to free up restricted flight paths is to use Global Positioning System satellites to locate aircraft precisely and then broadcast this information to other planes and controllers on the ground.

If the Bush administration decides to push ahead, it will most likely encounter the same objections that plagued its predecessor: that a commercialized ATC might protect the bottom line at the expense of safety or that other countries offer poor models for the busy U.S. system. True, negotiating the crowded airspace over Chicago or New York may be different from flying over Calgary or Quebec. But lessons from elsewhere still merit careful scrutiny to assess their applicability here. Despite protestations to the contrary, it's clear that the FAA isn't up to the job.

THE EDITORS editors@sciam.com

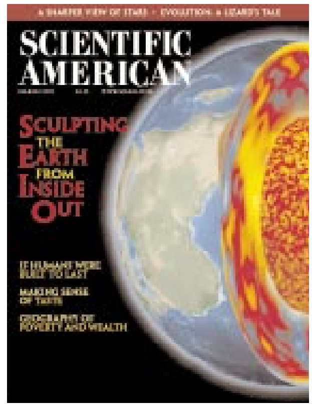
MARK WAGNER *Stone*

Letters

EDITORS@SCIAM.COM

MAKING SENSE OF WINEGLASSES: "In 'Making Sense of Taste' [March], David V. Smith and Robert F. Margolskee debunk the myth of the tongue taste map. But how," wonders Steve Bower of San Francisco, "does this mesh with wine lovers' belief that different glasses will direct wine to different parts of the tongue to impart a richer flavor? Is this merely a scam based on flawed research and perpetuated by snobbery and stemware manufacturers? Thousands of bar and restaurant owners eagerly await an explanation." Smith responds: "Depending on how the wine is distributed around the oral cavity, the access of volatiles to the nose via the retronasal route will vary. There are many flavors that folks recognize in wine—oak, fruitiness and so on—that are undoubtedly olfactory in origin."

Below, other fine notes regarding the March issue.

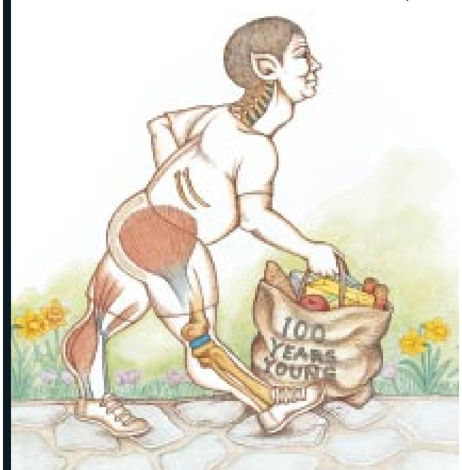


YOU, ONLY WITH A BETTER BRAIN

As an orthopedic surgeon, I spend a good deal of time battling potentially deadly hip fractures and arthritis ["If Humans Were Built to Last," by S. Jay Olshansky, Bruce A. Carnes and Robert N. Butler]. The biggest battle, however, is trying to change people's behavior after they incur small fractures that forecast larger, more dangerous ones. People keep their throw rugs and small pets to trip over, continue smoking, and remain inactive and overweight.

If we were really built to last, the most important fix would be a brain with a sense of self-responsibility and an understanding of risks and benefits, a brain that actually listened when our parents told us not to stick our fingers in the fan.

DON SAROFF
Santa Monica, Calif.



PATRICIA J. WYNNE

THE AUTHORS REPLY: It would be desirable to alter the vasculature of the brain in a way that would lessen the risk of stroke or suppress the proteins thought to be responsible for dementias such as Alzheimer's disease. But, as Saroff points out, our level of physical fitness and quality of life are to a large degree a matter of personal choice, not biological destiny.

INSTITUTIONAL POVERTY, INSTITUTIONAL WEALTH?

In "The Geography of Poverty and Wealth," Jeffrey D. Sachs, Andrew D. Mellinger and John L. Gallup emphasize geography to balance a long-standing overemphasis on institutions. But isn't much of the effect of geography connected with specific civilizations? The world's most energetic civilizations have made technological and cultural advances, and they have spread these advances via conquest, colonization and emigration. These civilizations have settled in regions that are easily accessible and healthy to live in, thus they have been the first to modernize while others remain scarcely changed.

If the U.S. were a traditional society rather than a democracy, would we expect notable differences in wealth between subtropical Florida, temperate and coastal Oregon, and inland Kansas? What would the authors say about inland but wealthy Switzerland as a counterexample to their geographic thesis?

FELIX GODWIN
New Market, Ala.

THE AUTHORS REPLY: Godwin is correct that the effect of geography may operate partly through institutional transmission. But much more is at play. In temperate-zone coastal East Asia, where European colonization did not occur, modern economic growth was also more readily achieved (Japan, South Korea, coastal China). Technological and institutional transfers from Europe and the U.S. were facilitated by a shared ecology, and problems of disease and food productivity were also more readily confronted. On the other hand, where European powers colonized tropical regions, the ecological constraints generally inhibited the transfer of technologies as well as institutions, and the burdens of tropical ecology on health and agriculture continue today. As for Switzerland, we can surmise that its being landlocked is less consequential because it is surrounded by rich countries and connected to them through the Rhine River Valley and overland routes. The impoverished landlocked countries of Latin America, Africa and Asia are surrounded by poor countries and are often burdened by high transport barriers even to their neighbors.

STARRING CHARA

In "A Sharper View of the Stars," Arsen R. Hajian and J. Thomas Armstrong failed to mention Georgia State University's CHARA Array on Mount Wilson, Calif. In terms of telescope aperture, number of telescopes, wavelength coverage, longest baseline and quality of site, the CHARA Array is arguably the world's most powerful optical interferometer for fundamental stellar astrophysics. We are also the only such project carried out solely by a university. Thus, we have a major role in training the upcoming generation of experts in this field.

HAROLD A. McALISTER
Center for High Angular Resolution Astronomy
Georgia State University

AFRICA RISING

Michael Gurnis ["Sculpting the Earth from Inside Out"] concludes that a mantle superplume has been pushing Africa upward for 100 million years. This implies that a single plume has been present under southern Africa for at least that long. How can this scenario be reconciled with the standard plate tectonic model, which suggests that the African plate has been moving rapidly to the northeast during that time? Has the plume drifted through the mantle to maintain its position below the continent?

JOHN LEVINGS
Jakarta, Indonesia

GURNIS REPLIES: We know from recent seismic images of the mantle that the African superplume tilts to the northeast. The giant structure begins at the core-mantle boundary under the South Atlantic and stretches upward to just below the Red Sea. Recent computer models offer an explanation for this tilt: the base of the plume has not changed position in the past 100 million years, but assuming that the plume is buoyant and slowly rising, the top of it would have spread out to the northeast as Africa moved in that direction—much the way a plume of smoke is smeared by a strong wind.

ERRATA In "A Sharper View of the Stars," by Arsen R. Hajian and J. Thomas Armstrong, the resolving power of the human eye would have to be 0.02 milliarcsecond to be able to see the individual atoms composing one's hand at arm's length.

In the illustration for the Lidar gun in "Gotcha!" by Mark Fischetti [Working Knowledge], the incoming optical pulse would be focused onto the avalanche diode, not the laser.

The article by Daniel Yarosh cited in "Skin So Fixed," by Julia Karow [News and Analysis], appeared in the March 24 (not February 9) issue of the *Lancet*.

50, 100 & 150 Years Ago

Comets ▪ State Security ▪ The Pharaoh's Emeralds

JULY 1951

ARTIFICIAL FIBERS—"Nylon, azlon, glass fiber, Vinyon, Orlon and other products have cascaded into the textile scene only within the past 15 years. Rayon, acetate and nylon have penetrated every wardrobe in the U.S., and the technological and military uses to which these and other synthetics have been adapted are legion. It is estimated that this year the world production of synthetic fibers will total more than three and one-half billion pounds, which means that they have outstripped wool and now stand second only to cotton and jute in the hierarchy of textile raw materials."

COMET COMPOSITION—"At great distances from the sun the comet would be inactive. But as it approached the sun the solar heat would vaporize the material on the surface of the nucleus from the solid state. The escaping gases would carry meteoritic material to form a meteor stream along the tail of the comet. The gases themselves would then be acted upon by the radiation of the sun. Its ultraviolet light would break down the molecules of CH_4, NH_3 and H_2O into simpler forms.

In this way we can account for the fact that the spectra of comets do not indicate the presence of CH_4, NH_3 or H_2O but do show the *radicals* of these compounds, such as CH, CH_2, NH, NH_2 and OH. —Fred L. Whipple."

JULY 1901

STATE SECURITY VS. TECHNOLOGY—"The inexplicable conservatism and arrogance of the Turkish customs authorities was recently shown by the prohibition of the importation of typewriters into the country. The reason advanced by the authorities was that in the event of seditious writings executed by the typewriter being circulated, it would be impossible to obtain any clew by which the operator of the machine could be traced. A large consignment of 200 typewriters was lying in the custom house at the time the above law was passed, and will have to be returned."

RACING CARS—"The Paris-Berlin motor carriage race was the most interesting ever held, from the point of view of its great distance of 744 miles, although it cannot be said that it was the most important for the industry, as the vehicles used in the race were not of a type which is desirable to develop. The racing vehicle is built purely for speed, and is a distinctive type, but is dangerous, unreliable and expensive, and makers object to supplying them, except to customers who are known to be expert chauffeurs. Our illustration shows the winner, Henri Fournier, and his chauffeur crossing the finish line in their Mors automobile."

PARIS TO BERLIN auto race, 1901

JULY 1851

STATISTICAL FILTH—"The 300,000 houses of London are interspersed by a street surface averaging about 44 square yards per house, of which a large proportion is paved with granite. Upwards of two hundred thousand pairs of wheels, aided by a considerably larger number of iron-shod horses' feet, are constantly grinding this granite to powder; which is mixed with from 2 to 10 cartloads of horse-droppings per mile of street per diem, besides an unknown quantity of the sooty deposits from half a million smoking chimneys. The close, stable-like smell and flavor of the London air, the rapid soiling of our hands, our linen, the hangings of our rooms and the air-tubes of our lungs bear ample witness to the reality of this evil."

THE MINES OF ZABARAH—"A most interesting discovery has been made in Egypt. In Mount Zabarah, on the Red Sea, is an emerald mine, which was abandoned in the last years of the reign of Mehemet Ali. An English company has resumed the working of this mine, which is believed to be still rich with precious stones. The engineer of the company has discovered, at a great depth, traces of an ancient gallery, which must evidently belong to the most remote antiquity. There they found ancient utensils and a stone upon which is engraved a hieroglyphic inscription, now partially defaced. It seems from the examination of this stone that the first labors of the mine of Zabarah were commenced in the reign of Sesostris the Great, who lived in about the year 1650 before Christ."

FROM *SCIENTIFIC AMERICAN*

ECOLOGY

Shrinking the Dead Zone

POLITICAL UNCERTAINTY COULD STALL A PLAN TO REIN IN DEADLY WATERS IN THE GULF OF MEXICO **BY SARAH SIMPSON**

SHRIMPERS may have to travel longer distances to find their catch because of Gulf hypoxia.

PHILIP GOULD Corbis

NEED TO KNOW: FACT VS. FICTION

The dead zone, also known as Gulf hypoxia, has doubled in size since researchers first mapped it in 1985. Despite this trend, last year's swath of oxygen-depleted bottom waters spanned a mere 4,400 square kilometers—only about one fifth of the record size in 1999. Because nitrogen inputs to the Mississippi River Basin have stayed constant, some people have falsely assumed that nitrogen must *not* cause hypoxia. In reality, factors other than nitrogen can cause the size of the dead zone to fluctuate. Midwestern floods in 1999 washed more nutrients down the Mississippi, for instance, and severe drought caused river levels to drop in 2000. Strong winds over the Gulf of Mexico can also resuscitate salty bottom waters by mixing them with the oxygen-rich river water that usually floats above.

VENICE, LA.—Zipping along in a 21-foot bay boat, we follow a muddy-brown finger of the Mississippi past golden-tipped marsh grass to the point where the river tickles the Gulf of Mexico. As the afternoon sun curbs the April chill, it is difficult to imagine that below the river's glassy surface lurks a deadly force. Every year this invisible menace creates a vast swath of oxygen-starved water along the Louisiana coast, suffocating billions of creatures by midsummer. Aptly dubbed the dead zone, this phenomenon hit record proportions in 1999 at 20,000 square kilometers—roughly the size of New Jersey.

Blame falls primarily on the 1.6 million metric tons of nitrogen—mostly fertilizer runoff from Midwestern farms—that pour out of the Mississippi and the nearby Atchafalaya rivers every year. State and federal officials finally agreed last October on a plan to curtail this recurring ecological disaster, known as hypoxia. But with no budget and no official committee to coordinate strategies,

OUT OF BREATH: Oxygen-starved gulf waters spanned 20,000 square kilometers in 1999.

MATT KANIA; SOURCE: NANCY RABALAIS

the plan is vulnerable to political whims. "This whole issue is being caught in that flux, so it's really hard to predict what will happen," says marine ecologist Nancy Rabalais, whose 16 years of work with the Louisiana Universities Marine Consortium brought the dead zone into the limelight.

The hypoxia problem begins when nitrogen and other nutrients wash down the mighty Mississippi to the Gulf of Mexico, where they trigger a bloom of microscopic plants and animals. The dead cells and fecal pellets of the organisms then rain to the seafloor. As burgeoning colonies of bacteria digest these tasty treats, they consume dissolved oxygen faster than it can be replenished. (Normal seawater, which typically holds about seven milligrams of dissolved oxygen per liter, becomes hypoxic when this value drops below two milligrams.) The flow of oxygen-rich water from the Mississippi cannot rectify the problem, because differences in temperature and density cause the warm freshwater to float above the cold, salty ocean water. Crustaceans, worms and any other animals that cannot swim out of the hypoxic zone will die.

Rabalais's campaigning began to pay off in 1998, when Congress ordered the Environmental Protection Agency to establish a task force to look at the problem. The task force used the recommendations of hundreds of scientists to design the current action plan and its key goal: shrink the yearly dead zone to fewer than 5,000 square kilometers by 2015—a significant reduction, considering that the running average from 1996 to 2000 was just over 14,000 square kilometers. Such a decrease could be achieved, the task force reported, by cutting the amount of nitrogen allowed to reach the gulf by 30 percent.

President Bill Clinton approved the action plan in January, but when he left office, those task-force members who were presidential appointees went with him. "There was a strong feeling among the task-force members that something like this needs to continue in order to coordinate the action plan," says Donald Scavia of the National Oceanic and Atmospheric Administration, who led the scientific assessment from which the plan evolved. By late May, President George W. Bush still had not appointed key officials who would have the authority to reconvene the task force.

Scavia also points out that President Bush submitted the federal budget for 2002 to Congress with none of the estimated $1 billion a year needed to finance the project. "It's a shame that we didn't get a budget [for the action plan] through sooner," Scavia adds, but he remains optimistic. "In the political arena here, you never know, but I think there's enough interest that it won't die."

According to NOAA, nutrient pollution has degraded more than half of U.S. estuaries. And in January the National Research Council named nutrient pollution and the sustainability of fisheries as the most important problems facing the nation's coastal waters in the next decade.

Gulf fisheries, which generate some $2.8 billion a year, are one potential casualty of hypoxia, but so far Louisiana fishers do not seem to be suffering. In fact, they may have an easier time making their quotas, because fish fleeing the dead zone tend to cluster along its edges. But that does not mean long-term damage isn't being wrought in the gulf, Rabalais cautions. "What we don't have data for is lost productivity," she adds. Hypoxia can block crucial migration of shrimp, which must move from inland nurseries to feed and spawn offshore. And in other places in the world, including the Black and Baltic seas, hypoxia has been blamed for the collapse of some commercial fisheries.

Flooding in the upper Mississippi this spring inevitably added higher-than-average nutrient loads to the river, leading some experts to predict that this summer's dead zone will be a big one. This month Rabalais and her colleagues will embark on a two-week cruise to see just how bad things have become.

RESUSCITATING THE DEAD ZONE

Several approaches could cut the amount of hypoxia-causing nitrogen released into the Mississippi River Basin. (Only a small fraction of these nutrients reach the Gulf of Mexico.) Numbers listed are annual savings in metric tons.

- Reduce use of nitrogen-based fertilizers, improve storage and use of manure, reduce runoff from feedlots. Amount cut: 900,000 to 1.4 million
- Plant perennial crops in lieu of fertilizer-intensive corn and soybeans on 10 percent of acreage. Amount cut: 500,000
- Remove nitrogen and phosphorus from domestic wastewater. Amount cut: 20,000
- Restore five million to 13 million acres of wetlands, which absorb nitrogen runoff. Amount cut: 300,000 to 800,000
- Divert rivers in coastal Louisiana. Amount cut: 50,000 to 100,000

SOURCE: National Science and Technology Council Committee on Environment and Natural Resources

SPACE

Sailing on Sunlight

A LOW-COST MISSION TO LAUNCH THE FIRST SOLAR SAIL BY MARK ALPERT

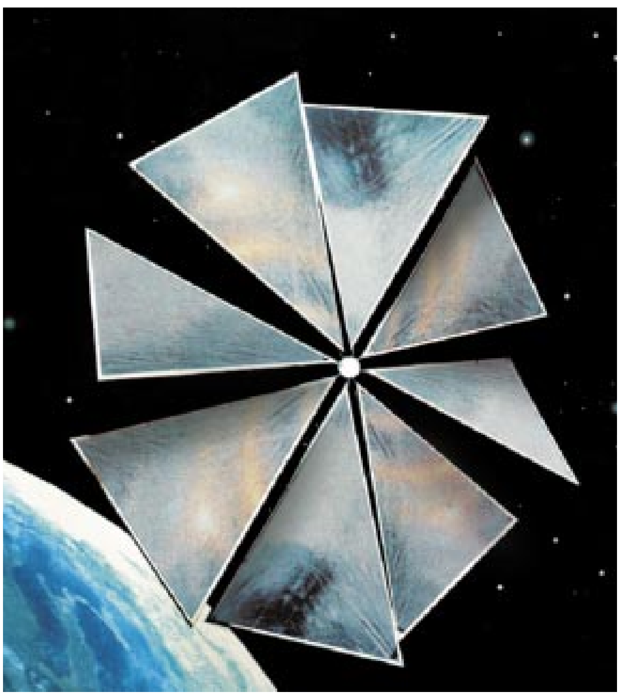
Pssst. Want to launch a spacecraft on the cheap? All you need is a group of space enthusiasts, a few million dollars and a Russian ballistic missile. The Planetary Society, a Pasadena, Calif.–based nonprofit organization dedicated to space exploration, is taking this low-budget approach to conduct the first demonstration of solar sailing—using the pressure of sunlight to propel a spacecraft.

The Planetary Society, which has more than 100,000 dues-paying members, contracted the Babakin Space Center, located just outside Moscow, to construct and launch its spacecraft. Russian scientists had proposed the idea of boosting the craft into orbit using a submarine-launched ICBM called the Volna. Arms-control agreements require the Russians to either discard the rockets or convert them to other uses. "We are literally taking these missiles out of the battlefield," says Louis Friedman, executive director of the Planetary Society. "The plan was so practical and inexpensive that we were able to find private funding for the mission."

That funding came from Cosmos Studios, a media company founded by Ann Druyan, the widow of Carl Sagan. The company furnished $4 million to develop Cosmos 1, a 40-kilogram spacecraft containing eight triangular panels of ultrathin Mylar. Once the craft is in orbit, it will unfurl the Mylar panels to form a 30-meter-wide sail that will be turned toward the sun. If all goes well, persistent pressure from the sun's photons will slowly push Cosmos 1 to a higher orbit. The goal of the mission is to sail the craft for one week, but it could conceivably keep cruising on the sun's rays for months.

So far, however, the progress of Cosmos 1 has been anything but smooth. In April an electrical short occurred during ground testing, damaging some of the craft's components and cables. The accident prompted the rescheduling of a suborbital test flight as well as the orbital mission, which is now planned for late this year or early 2002. For both the test flight and the orbital mission, the submarine launches will take place in the Barents Sea, north of the Russian port of Murmansk. Cosmos Studios will use images from both flights to prepare a two-hour documentary on the mission, which will be broadcast by A&E Television Networks next year. "It's amazing that a small company like ours could finance this," Druyan says. "I feel like I'm outfitting the Wright brothers' bicycle shop."

The great advantage of solar sails over conventional propulsion systems is that they do not require huge loads of rocket fuel. In fact, NASA is studying the use of solar sails to propel the Interstellar Probe, a mission tentatively scheduled for launch in 2010. A giant solar sail could accelerate the probe to speeds as high as 90 kilometers per second, allowing it to travel far beyond the solar system in just a few years. Cosmos 1 could serve as a stepping-stone for such efforts. Says Friedman: "I hope this will be the beginning of something grand."



COSMOS 1 will unfurl eight Mylar panels to form a 30-meter-wide solar sail.

COURTESY OF THE PLANETARY SOCIETY

BASICS OF SOLAR SAILING

The bigger the sail, the stronger the push. At Earth's orbit, the maximum thrust from solar pressure is only about nine millionths of a newton per square meter—equivalent to about one thousandth the weight of a paper clip. That's why NASA is planning to build a 400-meter-wide sail for the Interstellar Probe, which will be capable of traveling five times faster than any rocket-powered craft. Navigators will be able to tack the probe by adjusting the angle of its sail as it orbits the sun. Tilting the sail about 35 degrees away from the sunlight will maximize the thrust in the direction of the probe's orbital motion, causing it to spiral outward to the farthest reaches of the solar system and beyond.

HEALTH

À Votre Santé

SHOULD PHYSICIANS TELL SOME NONDRINKERS TO START? BY GARY STIX

Henny Youngman once quipped that when he read about the evils of drinking, he gave up reading. But reading and drinking may mix badly in another sense. When you read the conflicting messages about the health benefits of moderate drinking, you may throw down your newspaper in exasperation. It has been about 10 years since the "French paradox" became a sensation: the observation of a low incidence of heart disease in France, despite a *grande bouffe* of foie gras and other fatty Gallic foods. Researchers suggested that this may be attributable to high wine consumption. And the theory brought renewed vigor to the debate about the benefits of moderate alcohol intake.

WINE that maketh glad the heart of man.
—Psalms 104:15

The bickering continues. The 60-plus studies that establish links between moderate drinking and reduced heart disease have led some experts to claim that the weight of evidence is enough for physicians—on a case-by-case basis—to advise some teetotalers to drink moderately. This is a departure from previous medical counsel, which ran along the lines of: if you don't drink, don't start. At a recent conference in Palo Alto, Calif., on the effects of alcohol on health, sponsored by the New York Academy of Sciences (NYAS), Arthur L. Klatsky, a leading investigator on the epidemiology of alcohol, and physician colleague Roger Ecker presented an "algorithm" for helping physicians to advise patients.

This flow chart recommends moderate drinking (one to three drinks a week) for men between the ages of 21 and 39 and women between 21 and 49 who have coronary heart disease or two or more risk factors for it. In addition, it suggests that men who are 40 or older and women who are 50 or older should consider similar imbibing if they have heart disease or one or more risk factors for it. The chart makes exceptions for certain groups, such as pregnant women and recovering alcoholics. And Klatsky and Ecker emphasize that this advice doesn't obviate other preventive measures, such as stopping smoking.

This type of recommendation might still provoke a backlash from the medical establishment. Last January in its journal *Circulation,* the American Heart Association (AHA) urged physicians to emphasize to patients heart-protective measures other than drinking red wine that have a firmer grounding of scientific research: lowering cholesterol and blood pressure, for instance. The document noted that any benefits of drinking must be weighed against risks for conditions such as fetal alcohol syndrome and stroke.

The AHA advisory argued that more evidence is needed to prove the benefits hypothesized from the French paradox. Other lifestyle factors, such as a high consumption of fruits and vegetables among those studied, not the wine drinking, might play a role. Epidemiologists have acknowledged for a long time that, short of difficult-to-conduct randomized trials, solid confirmation of the salutary effects of alcohol may never be forthcoming.

A recent finding, however, about a genetic difference in the way people metabolize alcohol could help quell doubts about the epidemiology. Researchers from Brigham and Women's Hospital in Boston and the Harvard School of Public Health wrote in the February 22 *New England Journal of Medicine* that one form of the gene for the enzyme that breaks down alcohol, alcohol dehydrogenase, does its work more slowly than other forms of the gene. Those who have that gene and who drink moderately retain higher levels of high-density lipoproteins, the so-called good cholesterol, and face about half the risk of heart attack of drinkers without the gene. "This is kind of a poor person's randomized trial," said Harvard School of Public Health epidemiologist Meir J. Stampfer at the NYAS conference. "The gene is basically distributed at random with respect to behavioral characteristics, including alcohol consumption. So you can't argue that people with this gene exercise more or have a better diet."

If Stampfer is right, that may be good news for people who like to end the day with a nip. At a time when much hyped but little studied alternative medicine treatments may turn out to be nothing more than expensive placebos, a shot a day to keep heart disease away may hold increasing allure.

EVE TOWNSON *FPG*

DECANTING THE DATA

Most of the coronary benefits come from alcohol, not other components of various drinks.
—*British Medical Journal* (epidemiological review), Vol. 312; 1996

Something in wine in addition to alcohol may reduce the overall death rate for moderate wine drinkers.
—*Annals of Internal Medicine* (study of nearly 25,000 Danes), Vol. 133, No. 6; 2000

Growing evidence suggests that alcohol wards off heart disease by boosting levels of high-density lipoprotein cholesterol, thinning the blood or reducing insulin resistance.
—*Journal of the American Medical Association* (editorial), April 18, 2001

The major risk for moderate drinking is a 10 percent increase in the likelihood of breast cancer for women, which might be negated through increased folate intake.
—Meir J. Stampfer, New York Academy of Sciences conference, April 2001

ENERGY

Fuel Cell Phones

PORTABLE POWER FROM FUEL CELLS INCHES ALONG BY STEVEN ASHLEY

Micro fuel cells are being touted as the hot portable energy source of the future. They pack a lot more punch than batteries and yield only water as a by-product. Yet the revolution in small power sources is not likely to occur until the second half of this decade, when developers expect to unveil miniaturized fuel cells for third-generation cellular phones, laptop computers, personal digital assistants and other portable electronics. "Potential military and consumer users," reports Christopher Dyer, a fuel cell researcher and editor of the *International Journal of Power Sources,* "say they expect micro fuel cells to make inroads into markets now dominated by batteries within the next five years"—three years if key breakthroughs are made. As it stands today, prototype micro fuel cells still fall short of the mark.

Fuel cells are relatively simple devices that are similar to batteries. Both generate electricity chemically. And both depend on electrodes (an anode and a cathode) connected by an electrolyte. Fuel cells, however, convert hydrogen or hydrocarbon molecules rather than solid electrodes into electricity.

Fuel cells feature a specialized polymer or conductive liquid electrolyte that allows positive ions to pass but blocks electrons. Most micro fuel cell designs rely on a solid electrolyte called a proton exchange membrane (PEM) to create the charge separation.

The hard part in realizing the portable fuel cell future has been finding the best way to extract the energy. Larger fuel cells cannot just be scaled down. "As fuel cells shrink in size," Dyer says, "the engineering challenges multiply, requiring a difficult balance of providing sufficient power and convenience while minimizing the size and the cost."

Energy content is not the problem. In practice, a kilogram of hydrogen fuel can deliver from 1,000 to 23,000 watt-hours of energy, whereas the best lithium batteries now range from 175 to 300. But today's prototype micro fuel cells barely reach 100.

Although some developers are using hydrogen fuel stored chemically in canisters, most designers have opted for methanol, a cheap and widely available fuel. Breaking down methanol into hydrogen ions is chemically slow and thus limits power output. Platinum and ruthenium are typically employed to catalyze the reaction, but those elements are costly, so their use must be minimized, says Chao-Yang Wang, director of the Electrochemical Engine Center at Pennsylvania State University. Other problems include fuel leakage through the membrane, excessive heat buildup, moisture retention, and corrosion of the PEM by methanol. To avoid PEM degradation, most designers dilute methanol in water (to less than 5 percent), thereby yielding less energy. Many are working to make PEMs more robust. Robert Hockaday of New York City–based Manhattan Scientifics, for example, reports that his group has proprietary techniques that enable its cells to use 50 percent methanol fuel concentrations.

The final major design hurdle is to ensure that micro fuel cells can be manufactured at low cost. Manhattan Scientifics, Mechanical Technology in Albany, N.Y., and researchers from Motorola and Los Alamos National Laboratory are applying microchip fabrication techniques to their designs, an approach suited to low-cost, high-volume production. These integrated-circuit-like cells tend to produce small amounts of power, though.

Taking an entirely different design approach is Medis Technologies in Yehud, Israel. The Medis fuel cell, says the company's general manager, Zvi Rehavi, employs a liquid electrolyte, which avoids the PEM's drawbacks. It also relies on catalysts that incorporate extremely fine grained powders of electrically conductive polymers, thereby reducing the amount of expensive platinum-family metals needed. Medis has a deal with the Sagem Group (a French cell phone maker) and is building a pilot plant that can produce 50 million micro fuel cell units a year.

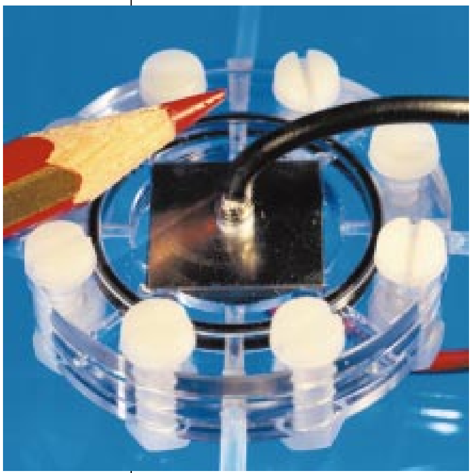
The Medis cell can also use ethanol for fuel—a useful feature for travelers. Says Rehavi: "I could pull a bottle of good vodka out of a hotel minibar, pour some into a fuel cartridge and place it in the fuel cell." Cheap vodka would presumably work, too.

NEED TO KNOW: STAYING POWER

Although micro fuel cells are likely to cost more than batteries, they will last much longer. Fuel cells can be replenished hundreds of thousands of times without degradation, whereas batteries typically can be charged only a few hundred times.

CIRCUITOUS JOURNEY

In fuel cells, electrons are freed from hydrogen fuel atoms at the anode, leaving positively charged ions. As the electrons travel through an outside circuit to power a load, the positive hydrogen ions head through the electrolyte toward the cathode, where the charged particles combine with oxygen drawn from the air to form water—the only waste product of fuel cells.



MICRO POWER: Tiny prototype fuel cell uses hydrogen gas to generate electricity.

FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS

news
SCAN

PRIMATOLOGY

Sigma Chi Chimpy

FORGET THE LADIES—FOR CHIMPS, HUNTING IS ABOUT FRATERNITY **BY MEREDITH F. SMALL**

The patrol of chimpanzees leaves early in the afternoon, silently moving through the forest in single file. After several hours, the hunters hear a troop of monkeys jumping nervously about the canopy. The chimps stop, grab one another and grin in anticipation of the feast to come. Then all hell breaks loose. The chimps shout a rallying cry and climb purposefully into the trees. The monkeys scream in alarm and mob the hunters, but to no avail. A male chimp grabs a monkey, swings it around and takes a bite. Soon, the carcass is torn apart and shared for breakfast.

Chimpanzees generally subsist on fruits, but they will hunt on occasion. Since 1963, when Jane Goodall first reported on chimp hunting at Gombe Stream Reserve in Tanzania, studies across Africa have confirmed that it is a male group activity and that red colobus monkeys are the preferred prey. In the 1970s primatologist Geza Teleki suggested that hunting serves two purposes: to fulfill protein requirements and, because the meat is precious, to gain mates.

But recently anthropologists John C. Mitani of the University of Michigan and David P. Watts of Yale University have discounted both those ideas. Instead they argue that hunting and meat sharing is simply a way for males to cement their relationships. Hunting, it seems, is not just for calories and not just to get girls. It is essential to the chimpanzee old-boy network.

For the past six years, Mitani, Watts and Jeremiah S. Lwanga, a Ugandan biologist, have been observing the largest-known group of chimpanzees at the Ngogo study site in Kibale National Park in Uganda. For 26 months during the late 1990s, the team saw chimps and red colobus monkeys together 192 times. Oddly enough, the chimps ignored the monkeys more than half the time. But when they did decide to hunt, the chimps were highly successful, catching and eating monkeys over 80 percent of the time. Given the chimps' kill rate, why don't they hunt all the time?

The researchers discovered that hunger had nothing to do with the decision; the apes went after monkeys when the forest was full of fruit. "They hunt when they are more likely to be successful, and that means in large groups. And it's only during the good times that large parties can form," Mitani explains.

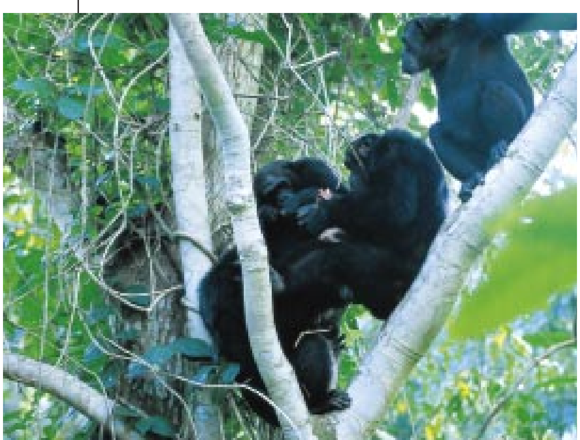
What about females? Primatologist Craig B. Stanford of the University of Southern California found that the mere presence of a female in heat predicted that males would hunt. And it's true, the Ngogo males sometimes preferentially shared meat with fertile females. But females in general didn't get much. Even begging didn't work. More significant, males who were nice enough to share meat with estrous females received no more matings than when they had nothing to give. "There are no immaculate conceptions in chimpanzees; if a chimp wants sex, he'll generally find a way to mate with a female," Mitani says. "And it doesn't appear that a male needs a chunk of monkey in his hand to do so."

More telling, Mitani and Watts found that the number of males in the group, not the presence of estrous females, best predicted active hunting. Males also shared meat more with one another than with any female, and they did so reciprocally: give me some of yours, and I'll give you some of mine. Those males who routinely shared the spoils also formed partnerships in other arenas; they groomed one another more often and aided one another in fights. "Chimpanzee hunting is not about using scarce and valuable resources to attract females," Mitani says. "It's about using this resource to form and build alliances with other males."

Meredith F. Small is a writer and professor of anthropology at Cornell University.

NEED TO KNOW: ALMOST HUMAN

The links between human hunting and chimpanzee hunting are fuzzy. "Chimps aren't necessarily good models for humans—we don't hunt in the canopy, and we don't have large canine [teeth]," explains David P. Watts of Yale University. And our hunting style may have developed long after we separated from the other great apes. But there are also meaningful connections. "The main importance for human evolution is in the social realm—the networks and male bonding," Watts says. "That's what goes on in our own species." Like it or not, the old-boy network is an essential part of life in the jungle and in the boardroom.



BONDING: Males share the spoils of the hunt.

GUNTER ZIESLER *Peter Arnold, Inc.*

Napoleon's Revenge

IN THE U.S., HEIGHT HITS ITS HEAD ON THE GENETIC CEILING BY ALISON McCOOK

In the early 1960s Wilt Chamberlain was one of only three players in the National Basketball Association listed at over seven feet. If he had played last season, however, he would have been one of 42. The bodies playing major professional sports have changed dramatically over the years, and managers have been more than willing to adjust team uniforms to fit the growing numbers of bigger, longer frames.

The trend in sports, though, may be obscuring an unrecognized reality: Americans have generally stopped growing. Though typically about two inches taller now than 140 years ago, today's people—especially those born to families who have lived in the U.S. for many generations—apparently reached their limit in the early 1960s. And they aren't likely to get any taller. "In the general population today, at this genetic, environmental level, we've pretty much gone as far as we can go," says anthropologist William Cameron Chumlea of Wright State University.

Growth, which rarely continues beyond the age of 20, demands calories and nutrients—notably, protein—to feed expanding tissues. At the start of the 20th century, undernutrition and childhood infections got in the way. But as diet and health improved, children and adolescents have, on average, increased in height by about an inch and a half every 20 years, a pattern known as the secular trend in height. Yet according to the Centers for Disease Control and Prevention, average height—5′9″ for men, 5′4″ for women—hasn't really changed since 1960. (Earlier maturation, increased life span and shifting demographics prevent overall trends in adults from matching those in children and adolescents.)

Genetically speaking, there are advantages to avoiding substantial height. During childbirth, larger babies have more difficulty passing through the birth canal. Moreover, even though humans have been upright for millions of years, our feet and back continue to struggle with bipedal posture and cannot easily withstand repeated strain inflicted by oversize limbs. "There are some real constraints that are set by the genetic architecture of the individual organism," says anthropologist William Leonard of Northwestern University.

Of course, to the human psyche, taller is often better. Popular figures ranging from athletes to fashion models to presidents are, for the most part, several inches taller than average. (Of the past 13 presidential elections, the taller candidate has won 10 times, the most recent exception being George W. Bush.) But this small group confuses the larger picture. In the case of NBA players, their increase in height appears to result from the increasingly common practice of recruiting players from all over the world. Indeed, almost half of all NBA players listed at over seven feet were born outside the U.S. Thus, it doesn't mean there are more seven-footers now than there were 40 years ago; rather, thanks to television, they are simply more noticeable, says Robert M. Malina, editor in chief of the *American Journal of Human Biology*.

Perhaps further clouding the fact that most Americans' height has remained stable of late are immigrants from countries where the growing environment has not improved as much as in the U.S. In these regions, the trend in growth has been much slower to start, nonexistent or, in cases of extreme malnourishment, even reversed. But when families move to the U.S., their children—exposed to hamburgers, hot dogs and other calorie-rich local fare—grow up to be a bit taller than their parents.

Genetic maximums can change, but don't expect this to happen soon. Claire C. Gordon, senior anthropologist at the Army Research Center in Natick, Mass., ensures that 90 percent of the uniforms and workstations fit recruits without alteration. She says that, unlike those for basketball, the length of military uniforms has not changed for some time. And if you need to predict human height in the near future to design a piece of equipment, Gordon says that by and large, "you could use today's data and feel fairly confident."

Alison McCook, a science writer based in New York City, is six feet tall.

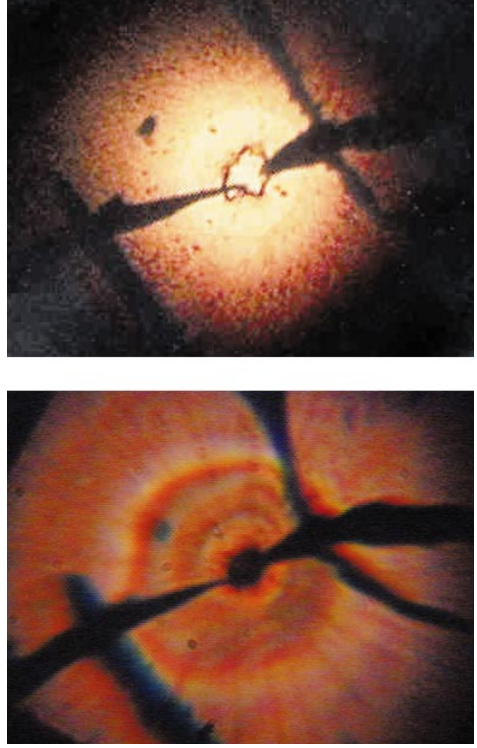
HIGHER UP: At 7′1″, Wilt Chamberlain was a rarity in the 1960s.

AP PHOTO

MOVING THE GENETIC MAX

The genes behind stature are distributed differently in each population. In one sense, a tiny percentage of Americans—perhaps overrepresented by basketball players—could possess genes that confer greater-than-average height. On a larger scale, this variation accounts for some of the ethnic differences in height: the average pygmy male is 4′9″, in part because his gene pool contains a different distribution of genes than that of Dutch men, who average about six feet. In theory, some kind of environmental or social force, such as widespread new diseases or shifts in immigration, would be needed to alter the prevalence of genes in a particular population.

PHASE CHANGE: Nitrogen is clear (*top*) but becomes opaque (*bottom*) when the pressure hits 1.93 million atmospheres. Dark forms touching the sample are electrodes.



DATA POINTS: SOMETHING TO HIDE?

Sheldon Krimsky of Tufts University and L. S. Rothenberg of the University of California at Los Angeles looked at policies in research journals regarding conflict of interest—whether scientists might benefit financially from positive results in their papers.

Number of journals sampled: 1,396

Number of journals that have a conflict-of-interest policy: 181

Number of articles in those journals: 61,134

Percent of those articles containing at least one disclosure of authors' financial interests: 0.5

Percent of editors who say they have rejected a submission based primarily on authors' financial interests: 18.8

Percent of journals whose request for disclosure came from:
Peer reviewers: 35.6
Editors: 48.8

SOURCE: Sheldon Krimsky and L. S. Rothenberg, "Conflict of Interest Policies in Science and Medical Journals: Editorial Practices and Author Disclosures," in Science and Engineering Ethics*, Vol. 7, No. 2; 2001.*

ELECTRONICS

Going Ballistic

Beating electrical resistance usually brings to mind superconductivity. But electrons can also travel unimpeded if they're in a wire so narrow that electrons can move in only one direction. Such quantum wires must not have defects or imperfections over their lengths that can trip up the electrons. (A quantum wire isn't considered superconducting because the electrons are not paired up in a way indicative of the superconducting state.) Past experiments, however, always revealed that such "ballistic" electrons encountered some resistance. Those speed bumps are now thought to arise from the contacts at the ends of the wire, not from the wire itself. Researchers from Lucent Technologies and Columbia University grew a layered structure that could conduct electrons ballistically and permitted the voltage in the wire to be measured without disrupting the flow. Their finding that the resistance is in the contacts only, described in the May 3 *Nature,* has implications for the design of future circuits based on quantum wires. *—Philip Yam*

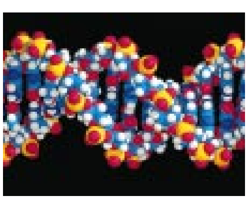
PHYSICS

A Crush on Nitrogen

Most things crack under pressure. Nitrogen prefers to turn into a semiconductor. Russell J. Hemley and his colleagues at the Carnegie Institution of Washington squeezed nitrogen gas between diamond faces, generating pressures up to 2.4 million atmospheres (240 gigapascals). The gas transformed into a semiconducting solid; what is more, the nitrogen stayed that way when the pressure returned to normal. This dense form of nitrogen might serve as a novel semiconductor as well as demonstrate what's inside the gas giant planets. The work, described in the May 10 *Nature,* also offers hope that hydrogen could be turned into a stable, solid metal that might exhibit room-temperature superconductivity or store energy in a compact way. *—Philip Yam*

GENOMICS

Bigger Snips of DNA



DNA'S A, C, T and G nucleotide bases can vary.

Although all humans share 99.9 percent of their genetic material, single-letter differences in our DNA sequences—known as single nucleotide polymorphisms, or SNPs ("snips")—ensure that each individual is unique. Unfortunately, these point variations can also predispose carriers to illness. Scientists studying descendants from northern Europe conclude in the May 10 *Nature* that the blocks of DNA that contain SNPs are eight times longer than earlier estimates pegged them to be. Thus, it should be easier than previously thought to link diseases to the DNA regions harboring the guilty SNPs. The length of these unbroken stretches of SNP-containing sequences also suggests that northern Europeans descended recently (in evolutionary time) from only a few common ancestors. *—Alison McCook*

MACMILLAN MAGAZINES LTD., © NATURE 2001 (*top*); KEN EWARD *Biografx/Photo Researchers, Inc.* (*bottom*); ILLUSTRATION BY MATT COLLINS

BEHAVIOR

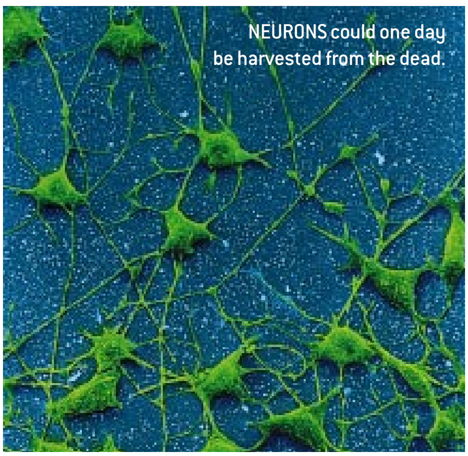
The Flipper Effect

Contrary to widespread reports, bottle-nosed dolphins have not passed the mirror self-recognition test—something only humans, chimps and orangutans have done. The study, by researchers from the Wildlife Conservation Society in New York City and described in the May 8 *Proceedings of the National Academy of Sciences,* found that dolphins that had been marked on their undersides and near their heads and fins spent considerably more time wiggling around in front of a mirror trying to inspect the marked areas than when they weren't marked. The investigators concluded that this behavior demonstrated that dolphins recognize themselves.

But such activity isn't evidence for self-recognition, say animal behaviorists Daniel J. Povinelli of the University of Louisiana at Lafayette and Gordon G. Gallup of S.U.N.Y. at Albany, who pioneered the mirror test in the late 1960s. Once familiar with mirrors, monkeys demonstrate "elevated looking times" when marked on their faces, Povinelli says, but they don't reach up to touch the mark—a key point in evidence for self-recognition.

Dolphins, of course, can't touch their own bodies, but it's possible to devise tests to see if, say, they try to brush marks off themselves, Povinelli notes. He and Gallup think that the "Flipper effect" is at work—the urge to believe that creatures as intelligent and engaging as dolphins must also be self-aware and empathetic. Dolphins may turn out to be able to recognize themselves, Gallup states, "but the data at hand are not definitive." *—Philip Yam*

SMART but not self-aware?



NEURONS could one day be harvested from the dead.

NEUROBIOLOGY

Born Again

Researchers led by Fred Gage of the Salk Institute have generated neural progenitor cells from a new source: human cadavers. Although previous attempts to cultivate this therapeutically useful material from dead brain cells were unsuccessful, the researchers found that when they added certain growth factors, they produced cells that could differentiate into functioning neurons and other brain cells. Clinical applications, such as using the cells for Alzheimer's and Parkinson's patients, are still a ways off. But harvesting stem cells from cadavers would get around the ethical concerns of using fetal cells. These results appear in the May 3 *Nature.*

—Alison McCook

GEOSCIENCE

Dwindling Albedo

One way to study the earth is to look at the moon. For more than 200 nights, researchers led by Philip R. Goode of the New Jersey Institute of Technology measured earthshine, the soft glow on the dark side of the moon created by sunlight reflected off the earth. The team found that the earth's reflective ability, or albedo, fluctuates and may be about 2.5 percent lower than it was five years ago. Interestingly, another recent study describes a previously disregarded influence on the earth's albedo: oceanic whitecaps. Apparently, the foamy crests of waves globally reflect about 15 million megawatts (or 0.03 watt per square meter), a climatic effect as influential as some greenhouse gases. The authors of both studies, which appear in the April 15 and May 1 issues of *Geophysical Research Letters,* say their results should be included in models of global climate change.

—Alison McCook

CLIMATE CLUES from earthshine.

WAYNE LEVIN *FPG* (*top*); QUEST/SPL/PHOTO RESEARCHERS, INC. (*middle*); ROGER RESSMEYER *Corbis* (*bottom*)

WWW.SCIAM.COM/NEWS

BRIEF BITS

- A study finds that **housing the mentally ill** is no more expensive than leaving them on the street. /050301/1.html
- Two laser beams interfering with each other to create a spiral of light and dark can **rotate microscopic objects** such as chromosomes. /050401/3.html
- Researchers have found a correlation between **early musical training** and the size of certain areas of the brain. 051401/1.html
- Infections can sometimes **fight tumors** by choking off the blood supply feeding the cancer. /050701/1.html

BY THE NUMBERS

In a Dry Land

THE SOUTHWEST FACES A DRY FUTURE, BUT THERE ARE WAYS TO COPE BY RODGER DOYLE

Agricultural economist Brian Hurd and his colleagues at Stratus Consulting in Boulder, Colo., have taken analysis of U.S. water resources to a new level. They have measured the sensitivity of each of the 204 hydrological areas in the lower 48 states to current climate conditions, an indicator of their potential vulnerability to global climate change. Their findings, summarized in the map below, are not good news for the Southwest, already famous for its long-standing water problems. Its 1996 drought, for instance, destroyed $3.6 billion in livestock and crops in Texas and Oklahoma alone. Groundwater tables in many sections have been sinking alarmingly; levels in some sections in the Great Plains Aquifer have fallen by 50 percent or more from the area's predevelopment levels. The region relies heavily on rivers and streams whose flow can vary greatly.

Among the hazards that the Southwest could face with the higher temperatures forecast for later in the century is reduced water flow in the Colorado River, which fluctuates by as much as 50 percent from year to year. If temperatures go up, particularly over the winter, more rain and less snow will fall. As a result, the mountain snowpack, which feeds the Colorado, will most likely melt earlier in the season and more quickly, leading to greater flooding and potentially less stored water to meet summer demands.

Despite this gloomy prospect, there is no unresolvable water crisis in the Southwest. Hurd and other experts believe that greater reliance on market pricing will lead to more efficient use and thus help to avoid economy-crippling water crises. Federal water subsidies to farmers encourage unrealistically low prices. In addition, outmoded state laws, such as those that prohibit users from selling water saved through their own conservation efforts, inhibit a free market. Hurd also emphasizes the importance of better management of aquifer and groundwater systems and development of more efficient practices and technologies, such as water-recycling equipment that will better cope with water shortages.

More accurate forecasts of climate and water demand will help as well. Although hydrological science has come a long way since the 1950s, when experts forecast U.S. water consumption by 2000 at a level three times the actual rate, there is considerable room for improvement. With better predictions, for example, farmers might sow less water-thirsty crops, and municipalities could plan ahead to ensure adequate supplies.

The population of the Southwest is projected to rise 40 percent over the next 25 years, an increase that may seem unsupportable. But with proper conservation measures, there is no objective reason that such growth cannot be achieved without unacceptable environmental strain. Statistics suggest that considerable leeway exists: the Southwest consumes 1,630 gallons a day per capita, whereas Israel consumes 260.

Rodger Doyle can be reached at rdoyle2@adelphia.net

NEED TO KNOW: THIRST OF A NATION

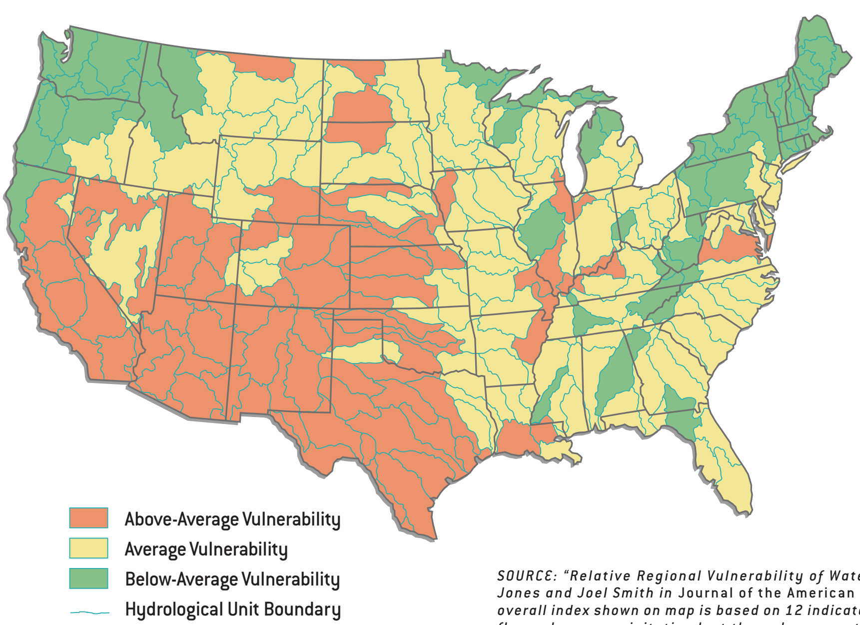
Number of gallons of water Americans use a day, 1995:
Total: 402 billion
Surface water: 324 billion
Groundwater: 78 billion
Percent from freshwater: 84.8
Percent from salt water: 15.2

Where the water goes (percent):
Power generation: 47
Irrigation: 33
Public use (mostly households): 11
Industry: 7
Livestock: 1

Per capita consumption, gallons a day:
U.S.: 1,500
In the nine most water-stressed states (Arizona, California, Colorado, Kansas, Nevada, New Mexico, Oklahoma, Texas, Utah): 1,630

Recent conservation efforts seem to be working: total U.S. use in 1995 was 2% less than in 1990 and 9% less than the all-time-high level of 1980

VULNERABILITY OF WATER RESOURCES TO CLIMATE VARIABILITY



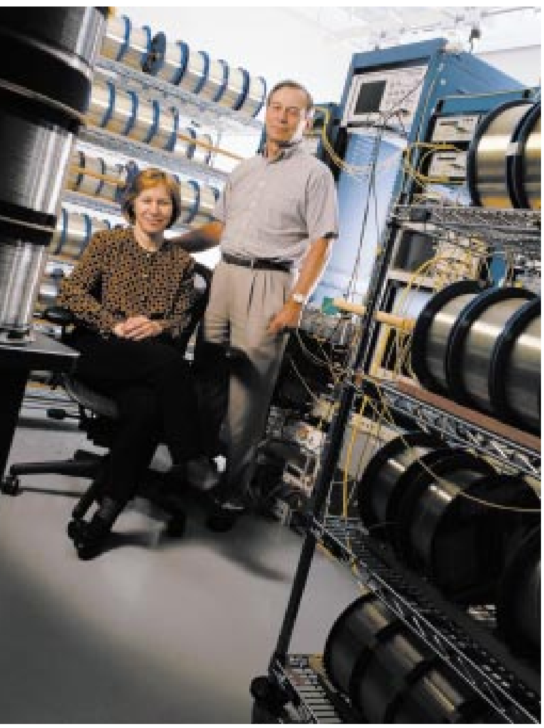
SOURCE: "Relative Regional Vulnerability of Water Resources to Climate Change." Brian Hurd, Neil Leary, Russell Jones and Joel Smith in Journal of the American Water Resources Association, Vol. 35, No. 6, December 1999. The overall index shown on map is based on 12 indicators, including groundwater and surface-water withdrawals, streamflow volume, precipitation lost through evaporation, barriers to water trading, share of industrial water not recycled, expenditures on dredging navigable waters, extremes of heat and cold, dissolved oxygen in water, and species at risk. Map reprinted with permission of the American Water Resources Association.

MATT KANIA

Builders of Light Pipes

Structured teamwork propels Corning beyond commodity fiber By GARY STIX

Optical fiber is the plumbing of the Internet age. And Corning is the world's biggest plumbing supply house, holding about 40 percent of the market for optical fiber. During the past five years, it has mounted a successful campaign to revamp its standard fiber products, descendants of the first commercial light pipes patented by the company about 30 years ago.



FACILITATORS: Cynthia Giroux and Jan Conradi helped develop a new optical fiber at Corning.

FOREST McMULLIN

Despite the encomiums of New Economy proselytizers about radical change, Corning achieved this goal of making premium fiber by streamlining traditional management techniques, using structured product-development formulas that would be recognizable to Frederick Taylor, the 19th-century father of management science.

One project began in 1998, when Wendell P. Weeks, then Corning's senior vice president of opto-electronics, pressed subordinates to think of new fibers that would help implement his vision of an all-optical network in which an optical signal could travel the length of the network without the costly need to be reconverted into an electrical one to amplify a signal or restore the shape or timing of digital pulses. A piece of this strategy was a complete overhaul of metropolitan-area networks—regional fiber installations in cities and suburbs that might, for example, tie together separate corporate campuses or hook up distributed-data storage facilities.

Weeks had pounded away at his staff about how all-optical networks would arrive in the metro area and how a new type of fiber would be needed to meet the demands of this market. Much of his staff was skeptical because fiber links on metro networks tend to be short, a few tens of kilometers at most, and the standard fiber, called single mode, works well for these applications. At one meeting, Weeks remembers, a subordinate, Gerald J. Fine, head of Corning's photonics division, finally blurted out: "I've been listening to this meeting after meeting, and I don't know what you're talking about."

Weeks realized that he needed to prove his case to his own staff with more than bluster. He initiated what Corning calls in-house an "innovation"—a formal step-by-step process that begins with an assessment of the validity of an idea and then, if warranted, moves through sequential stages of research, development and manufacturing. It gives ample opportunity for a bailout if flaws in the plan become evident. Innovation, for which development teams go through one-day training classes, is just one of the terms in Corning's team-building dialect used to describe bringing a product to market. It is hard to talk to an employee at any length without hearing about a "value proposition" (how a product benefits a customer) or "shooting ahead of the duck" (anticipating where the market is going).

Corporate argot is just one manifestation of an insular regimentation that the company has used to accelerate product development. Today it takes a year to develop a new fiber, not the three to five years it once did. This emphasis on process and procedure won Corning the coveted Malcolm Baldridge National Quality Award in 1995.

The project team Weeks deployed quickly realized that metro fiber networks occupy a niche in optical communications distinct from capital-intensive long-distance transmission. "We found that there were five particular attributes we had to look at," says Jan Conradi, director of strategy for Corning optical communications.

"They were cost, cost, cost, cost and cost."

The metro networks used inexpensive distributed-feedback lasers that could transmit only a limited distance because of a characteristic of the optical signal called chirp. Optical pulses that carry digital information are composed of multiple wavelengths. Chirp causes the wavelengths on the leading edge of a digital pulse to grow shorter (a shift toward the blue end of the spectrum) and on the trailing edge to grow longer (a shift toward the red). As a result, the pulse spreads out rapidly because the blue wavelengths travel faster than the red ones. Eventually one pulse merges with another, cutting down on how far a signal can travel before its information becomes unintelligible.

The team began to explore what characteristics in a fiber would counteract chirp. Coincidentally, Conradi had examined that problem, not in the laboratory but in a graduate-level course on telecommunications that he had taught until a year or so earlier at the University of Alberta. He dug out a textbook from his attic, *Laser Diode Modulation and Noise,* by Klaus Petermann. It contained an equation that showed how chirp could be neutralized by designing a fiber with so-called negative dispersion that would counteract the chirp-induced spreading of the pulse, allowing the signal to travel farther. In such a fiber, the blue wavelengths travel more slowly than the red ones, so a pulse gets compressed.

The equation—along with some additional modeling work in Corning's Sullivan Park research center in Corning, N.Y.—showed that in negative-dispersion fiber, a signal could travel up to 10 times farther without having to be converted to an electrical signal to correct dispersion. A few days later Corning brought these results to one of its telecommunications customers. "Their response was that this could change the game," Conradi says. Silence filled the room as the Corning engineers and marketers who had just heard this comment mulled over this early confirmation that Weeks's perception had been on the mark.

In the intensive middle phases of Corning's five-stage commercialization process, groups work in cross-functional teams that include development engineers as well as marketing and manufacturing specialists. This stage is when developers must concoct reasons why the project shouldn't move forward—and then shoot down these objections. "The process wasn't really that friendly," says project manager Cynthia B. Giroux. "Product development is like linking arms and jumping off a cliff and having faith that the parachute will open."

An internal analysis compared different types of fibers and lasers with respect to signal speed, distance traveled and amount of spacing between transmission channels. One question the group addressed was whether existing products—such as standard single-mode fiber or a then new premium long-haul fiber called LEAF—would do the job just as well. Negative-dispersion fiber was, in fact, an unusual design that had been used only in ultralong-distance undersea links.

PULLING a fiber

Product development is like jumping off a cliff and hoping the parachute will open.

But with its ability to carry light long distances and reduce overall system costs, this type of fiber, which the team named MetroCor, remained the first choice. Debate also focused on how much capacity the networks would need; in the end, the group chose a fiber optimized for a 2.5-gigabit-per-second data transmission rate instead of the higher 10-gigabit speed.

Such technical decisions can actually make or break a new product line. Lucent Technologies's choice of networking equipment that had too little transmission capacity was a factor in the company's current financial straits. During development, Corning collaborated with customers to probe how the new fiber worked with the networks they build. Its photonic test center in Somerset, N.J., allows a company to install its networking equipment for testing with Corning fiber.

As a product gets closer to launch, Corning, whose manufacturing facilities are located in Wilmington, N.C., tries to eliminate the stark line between development and manufacturing. It has done so by building a virtual mirror image of each operation. It has full-scale glass-making equipment and a five-story-high fiber-drawing (-pulling) tower at its Sullivan Park research facility, which allow the company to make fiber and identify manufacturing problems before they reach the plant. Meanwhile part of the development team works at the manufacturing plant to facilitate the handoff.

Even in mid-February of 2000, with the manufacturing line ready to start in two weeks, Giroux's team wrestled with last-minute glitches that could have impeded a signoff on the final specification delivered to the Wilmington plant. At that time, it had only just found a solution to a "critical optical parameter" that helped to avoid "throwing away a lot of glass" after the manufacturing line cranked up, Giroux says.

The plant started cranking out fiber in March of last year and has shipped hundreds of thousands of kilometers of MetroCor since. The fiber appears to be selling more briskly than any previous product, spurred by its ability to reduce optical-networking costs by up to 40 percent. This obsession with innovation accounts for a shift that has seen new products (those less than four years old) go from 30 percent of the company's portfolio five years ago to 80 percent today. This year Corning plans to release 12 new or enhanced fibers, each one having been shepherded through the careful process from idea to invention to a product that serves as the plumbing for the infrastructure of broadband networking. SA

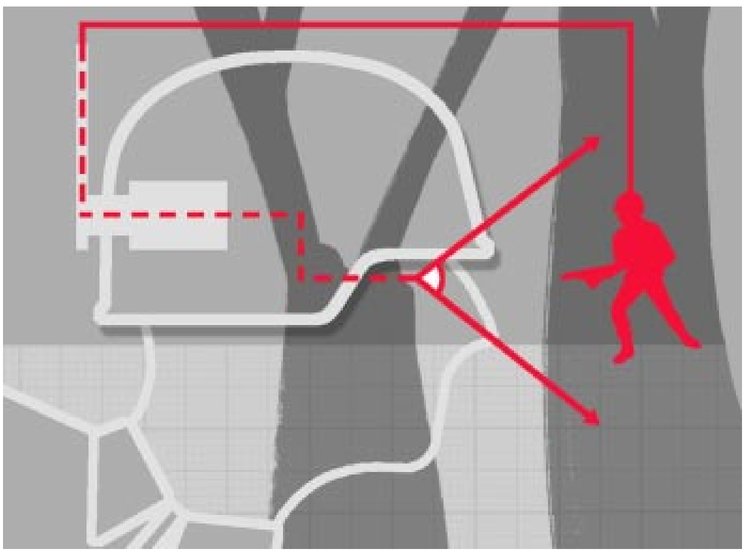
CORNING

Sounding Out Snipers

Drawing a bead on urban warriors who take potshots at regular troops   By GARY STIX

From the halls of Montezuma to the streets of Sarajevo, battle readiness now requires preparation for urban warfare, as troops increasingly confront both peacekeeping and routine military operations in cities. Anticipating this need, the Defense Advanced Research Projects Agency commissioned prototypes for an array of specialized technologies to assist the military's street-fighting man in shutting down sniper fire.

A sniper-detection device developed by BBN Technologies, part of Verizon, allows soldiers to track the trajectory of a bullet back to a hidden enemy, using microphones and a compass mounted on a helmet. Alternatively, these sensors could be installed on a truck, aircraft, streetlight or even a building facade's ornamental gargoyle. The bullet tracker works when two or more sensor-equipped soldiers pick up the acoustic vibrations from both the muzzle blast (the gunpowder explosion as the bullet leaves the weapon) and the supersonic crack as the bullet speeds along. The sensors can then radio their data to computers that soldiers wear on their bodies. A computer's mathematical model, in conjunction with the Global Positioning System, then overlays the information on a map. From these data, the model estimates the trajectory, caliber and speed of the bullet, the distance it traveled and the elevation of the sniper. Even if sensor inputs from only one soldier's helmet are available, the system can provide some of these results.



JOHN McFAUL

The BBN detector can purportedly track snipers at greater distances than other prototype systems. It also uses inexpensive microphones and simpler computers than other sniper detectors. And unlike most of its competitors, the tracker will still work if it is unable to pick up the muzzle blast, as is the case if the gun is equipped with a silencer or if the acoustic waves are blocked by buildings before reaching a sensor. Gregory L. Duckworth, James E. Barger and Douglas C. Gilbert received the patent (U.S.: 6,178,141) and assigned it to BBN. (Barger was one of the researchers who did an acoustic analysis of the gunshots that killed John F. Kennedy.) DARPA financed their work as part of a program designed to respond to the sniper problems confronted by troops in the Balkans.

Tracking the sound of gunfire is one thing. Faking it is another. Three inventors for the U.S. Army Research Laboratory—Carl Campagnuolo, James Chopack and Jonathan Fine—received a patent (U.S.: 6,198,404) for audio decoys that can be dispersed throughout an area where enemy troops are encountered. The patent was assigned to the U.S. Army. A retreating scout unit or special-forces contingent can activate individual decoys by a remote radio link. The decoys play a digital recording of the sounds of an M-16 or a machine gun, helping to divert the enemy. On the new technological battlefield, survival may sometimes depend less on superior firepower than on detection and mimicry of the tat-tat-tat of automatic weaponry. SA

Please let us know about interesting or unusual patents. Send suggestions to: patents@sciam.com

Starbucks in the Forbidden City

Eastern and Western science are put to political uses in both cultures By MICHAEL SHERMER

In the sixth century B.C., Siddhārtha Gautama—better known as the Buddha—extolled the virtues of enlightenment through a "middle path":

> Avoiding the two extremes the Buddha has gained the enlightenment of the Middle Path, which produces insight and knowledge, and tends to calm, to higher knowledge, enlightenment, Nirvana. This is the noble Eightfold Way: namely, right view, right intention, right speech, right action, right livelihood, right effort, right mindfulness, right concentration.

Twenty-six centuries later American physicist Murray Gell-Mann constructed a subatomic model he playfully called the Eightfold Way, because it consisted of eight particles with eight possible rotations. The name was a joke, he told a Caltech audience in a lecture on "Quantum Mechanics and Flapdoodle," referring to the New Age fiddle-faddle about his theory presented in books whose authors didn't get the humor and thus constructed elaborate and imaginary links between Eastern mysticism and Western science. Such comparisons do tug at one's inner sense that the continuities between Eastern and Western worldviews should reflect some deeper structure, but is it really possible (in an analogy to the uncertainty principle in quantum mechanics) that the orbit of Mars, like the orbit of an electron, is scattered randomly around the sun until someone observes it, at which point the wave function collapses and it appears in one spot? No. Quantum effects wash out at large scales. Microcosms do not correspond to macrocosms. And the vague similarities between Eastern and Western models result from the fact that there are only so many variations on explanations of the world; by chance, some are bound to resemble one another.

I was struck by such East-West contrasts and continuities on several levels during a recent trip to Beijing for the International Conference on Science Communication (which for much of China means such scientific basics as birth control). The conference was held in a sleek downtown high rise, but the projectors routinely broke down during presentations. Throughout the city, bicycles far outnumber cars, buses and taxis. Businessmen and women, before cycling to their jobs, flock to city parks to perform tai chi, the ancient art of adjusting one's spiritual energy. Buildings and homes incorporate the latest Western amenities but do not neglect *feng shui* in their architectural design, out of fear for energy blockages at inappropriately located doors and walls.

A tour of the Great Hall of the People at Tiananmen Square (communism at its worst) forces visitors to exit through a basement filled with kitschy crafts of the tackiest sort (capitalism at its worst). The Museum of Science and Technology fea-

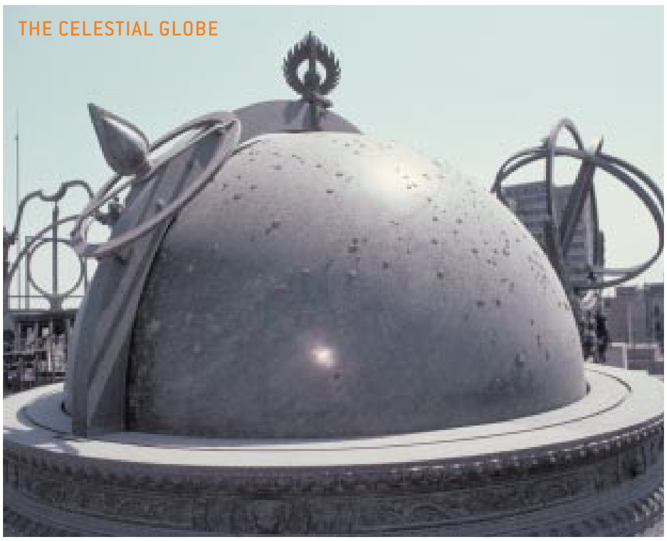
BRAD HINES (*top*); GUANG NIU *Reuters*, © REUTERS NEWMEDIA, INC. *Corbis* (*bottom*) tured an old, faded IMAX film (*The Dream Is Alive*) projected onto a water-stained, chipped-tile ceiling; a fabulously clever pneumatic bed of nails would have demonstrated the harmless distribution of mass over many points—if only it had worked. Even in the Forbidden City—where emperors and empresses, concubines and eunuchs, palanquins and peons roamed for five centuries—there could not have been a more striking contraposition in the only store I found in the palace interior: a Starbucks! Of course, I had to imbibe.

For my yuan (80 to a dollar), however, the finest example of contrast and continuity was the Ancient Beijing Observatory, built in 1442 for the sixth Ming dynasty emperor, Zhengtong. Located on the main east-west corridor of the city (itself laid out according to celestial coordinates) on the roof of what was once a tall building, this observatory contains a sextant, a theodolite, a quadrant, an altazimuth, several armilla and a celestial globe, allowing Chinese astronomers to track the motion of planetary bodies, to record eclipses and comets and to mark the location of the Milky Way galaxy and the constellations. It was the Keck Observatory of its age, measuring, for instance, the length of the solar year at 365.2425 days, off by only 26 seconds. Its beautifully crafted bronze instruments starkly oppose the steel girders and scaffolding that abound in nearby high-rises.

A closer examination of these astronomical instruments, however, reveals connections to Western science but with instructive differences. The rings of the armillary sphere are divided into 360 degrees—a European tradition adopted from Mesopotamian geometry—instead of 365.25 daily segments, as found in purely Chinese instruments. The celestial globe presents the Milky Way galaxy in dimpled metal; rough-cut metallic stars mark the familiar constellation Orion, including the unmistakable belt stars, brilliant Sirius, giant Betelgeuse and Rigel. Even the Orion nebula is visible below the belt.

But something is amiss: Orion is backward. Betelgeuse should be in the upper left corner of the constellation, not the right, and Sirius should be to the left of the belt stars. The sky is inside out. According to archaeoastronomer Ed Krupp, all celestial globes are constructed from the "transcendental eye's view" of an outsider looking in. It turns out that this celestial globe (along with the rest of the instruments) was built in 1673 during the Qing dynasty by a Belgian Jesuit named Ferdinand Verbiest and, in Krupp's words, "blends a clearly Western pedigree with representations of traditional Chinese constellations."

THE CELESTIAL GLOBE



ROGER RESSMEYER *Corbis*

Such celestial precision was not needed for any scientific reasons in these early centuries. Rather, as Krupp explains in his insightful book on the politics of astronomy, *Skywatchers, Shamans, and Kings,* "as a truthful mirror of nature, astronomy was official business, a tool in the service of the social and political agenda of the state." Astronomical accuracy was "celestial certification of imperial power." The emperor was supposed to be the son of the celestial god Shang Di, and thus state-sponsored astronomy validated his link to the highest order and solidified the connection he represented between heaven and earth, sacred and profane, macrocosm and microcosm. China was the "middle land," the center of the world, with the Tiananmen "Gate of Heavenly Peace" leading into the Forbidden City (itself aligned by the cardinal directions), followed by the "Hall of Supreme Harmony" (due north on the cosmic axis), where the emperor held audiences to announce the calendar, new year and winter solstice.

In parallel fashion, during the conference on science communication, a delegation of representatives from Chinese and American scientific organizations had an audience with one of the top ministers of the Chinese government, which amounted to little more than a bureaucratic formality of tea and polite dialogue. As we patiently listened to the translation, I was struck by the symbolism: because science is now the connection between the sacred and the profane in a secular scientific society, it must be part of official state business—a certification of political power, be it monarchical Europe and imperial China, or capitalist America and communist China. Whereas some East-West comparisons, such as the Eightfold Way of physics, are chimerical, others are not, particularly those of a political nature, for, as another ancient philosopher, this one from the West, observed: "Man is by nature a political animal." SA

Michael Shermer is the founding publisher of Skeptic *magazine (www.skeptic.com) and the author of* The Borderlands of Science.

A Mind for Consciousness

Somewhere in the brain, Christof Koch believes, there are certain clusters of neurons that will explain why you're you and not someone else By JULIE WAKEFIELD

LOS ANGELES—Prominent on Christof Koch's desk is a white ceramic phrenology bust, its skull divided by glazed black lines into arbitrary regions. The maverick neuroscientist assures me that I need not worry about any caliper exam; he is as bemused as the rest of us by Lorenzo Fowler's 19th-century phrenological propaganda that cortical areas correspond to such personal attributes as "love of country" and "secretiveness." But Koch appreciates the early brain map as a reminder that he's looking for "a discrete set of neurons that might be in 20 different areas but share some set of properties that are responsible for generating consciousness."

CHRISTOF KOCH: NEURONAL CORRELATES

- **Admired designs: Golden Gate Bridge, Boeing 747, Apple Macintosh**
- **Daily routine: Running in the mountains with one of his three large dogs**
- **Top priorities: Wife, Edith, a nurse; children Alexander, 18, and Gabriele, 17**
- **Recent excursion: Israel, where he and Alexander helped archaeologists excavate Herod's Temple. "It gives you perspective, digging in the ashes of people who thought they were the pinnacle of human civilization."**

Koch, 44, directs the computation and neural systems program at Caltech. He arrived here in 1986, a time when consciousness research was still considered career suicide even for established brain researchers. But high-profile attention to the subject by Nobelists Gerald M. Edelman and Francis Crick, coupled with advances in functional brain imaging, has elevated the field—and its investigators—to respectability. Neurobiologists have since given up the notion that Koch may be dangerously offbeat, despite his having tattooed his arm last summer with the Apple Computer logo to demonstrate his love of the Macintosh (a zeal not even matched by Steve Jobs). The neuroscientist leads about 20 researchers and calls their mission to explain consciousness "one of the major unsolved problems of modern science."

During his early years, Koch, the American-born son of German diplomats, imbibed embassy life from Kansas City to Amsterdam to Bonn, Ottawa and Morocco. Initially he wanted to be a cosmologist, but he realized that his gifts were not in high-level mathematics. Two books sparked his interest in nervous system computations, one of which gave a physicist's perspective on the brain. Its author, Valentino Braitenberg, became one of Koch's advisers at the Max Planck Institute for Biological Cybernetics in Tübingen, Germany, where Koch earned a doctorate in physics in 1982.

Koch started thinking about consciousness seriously in the summer of 1989—thanks to a throbbing toothache. He wondered, Why do a bunch of neurons flashing around result in pain? And why don't electrons moving in a transistor cause the computer to have subjective states? By that time he and Crick, one of DNA's co-dis-

PHOTOGRAPHS BY CATHERINE LEDNER

coverers, had already had several discussions along these lines (they had met incidentally in Europe and become friends). They soon drafted their first joint paper on consciousness.

Visual awareness is Koch's chief pathway into the murky workings of the mind. Not only is vision readily manipulated and the best understood of the senses, but it also shares fundamental aspects among species ranging from fruit flies to humans. Such commonalities are important to Koch because he believes (to the chagrin of many philosophers) that facets of consciousness—visual, olfactory, linguistic, even self—are all "elaborations of a common biological process." Koch has used electrophysiological recordings and brain imaging in primates to explore the neuronal operations underlying vision.

Along the way, his vision work has helped elucidate how neurons compute. Koch was among the few to challenge the prevailing metaphor equating the wiring of the human brain with the circuitry of a computer. Instead of accepting the idea that thought results from the combined action of billions of neurons, each a relatively simple component, he asserted that individual neurons carry out complex computations.

Indeed, mounting evidence shows how neural cells function not only as a network of linear threshold devices, relaying electrical pulses or not, but also as individuals working autonomously and adaptively. Neurons can add signals, subtract them, multiply, divide, filter and average them, among other functions. "The computational toolbox of individual neurons dwarfs the elements available to today's electronic circuit designers," Koch says.

BUSTED: Phrenology is discredited, but to Koch it suggests a way to think about consciousness.

In their continuing collaboration, he and Crick seek to understand visual consciousness at the neuronal level. So far they have issued several bold and controversial hypotheses that describe how neurons correlated with consciousness may be identified. The first, proposed in 1990, pertains to the existence of an oscillation and synchronization pattern among groups of neurons during visual stimulation. In recent years the researchers have reformulated this claim, contending that neurons exhibit two forms of activity. Both can lead to behavior, but only one gives rise to subjective states of consciousness. And it is that state that is associated with synchronized neuronal firing.

To test such notions, Koch is focusing on the cagey mind of the rodent. His team aspires, among other things, to create "zombie" rodents by inactivating specific subpopulations of neurons, thereby dissociating the animals' behavior and awareness. In this way, neurons critical for awareness may become apparent. (But first the team must show that rodents are indeed conscious, through experiments based on a more complex version of Pavlovian conditioning called trace conditioning.) Unraveling basic neural correlates, Koch believes, will definitively answer such questions as whether human babies are conscious.

When it comes to a grand unified mind and brain theory, or GUMBAT, in Koch's lingo, Koch and Crick feel that humility is in order. "The last 2,400 years—starting with Socrates, Plato and Aristotle—have shown the futility of developing grand-scale theories," Koch says. "Right now we feel we lack basic elements for any such theory." He equates pursuing a global model now with "Aristotle's chances of developing a good theory of heredity in his day."

Not all leading consciousness researchers think that locating specific neuron groups is the key. Edelman and his longtime collaborator Giulio Tononi, now at the University of Wisconsin–Madison, see limits. "Even if we could come down with a small list [of neurons]," Tononi says, "we wouldn't understand why some neurons contribute to the whole experience of consciousness and others don't. The apparent differences seem insufficient to explain the metaphysical gap." Tononi and Edelman favor characterizing broader neural processes to account for properties of consciousness—namely, differentiation (neural complexity) and integration (functional clustering). That is, a huge number of conscious states exist, and each is a unified whole that can't be subdivided. These two properties, they contend, can be measured to gauge whether a group of neurons is contributing to conscious experience. The combination of neural complexity and functional clustering forms the basis of their so-called dynamic core hypothesis.

Meanwhile a chorus of philosophers led by David Chalmers of the University of Arizona believes that a scientific theory of consciousness will emerge but that it won't be just a neurophysiological theory. "It's very much an open question what form" a theory of consciousness will take, Chalmers remarks. Before a theory can take hold, he and Roger Penrose of the University of Oxford propose that new physical laws or principles will need to be discovered. That's because consciousness, they say, is an irreducible phenomenon, much like space, time and gravity.

Koch acknowledges the difficulties in developing a neurophysiological explanation of subjective experience but thinks neuroscience will eventually solve the puzzle. "Whether we will ever have a satisfactory reductionist account, like we think we do of life, remains an open question," he says. Then he points to a bit of wisdom from renowned English biologist J.B.S. Haldane. "The universe is not only a strange place," Koch paraphrases, "but a stranger place than we can imagine." SA

Julie Wakefield is a science writer based in Washington, D.C.

How to Build a HYPER computer

BY THOMAS STERLING

The simulation and ultimate solution of humanity's major ills and most perplexing problems require significantly faster supercomputers

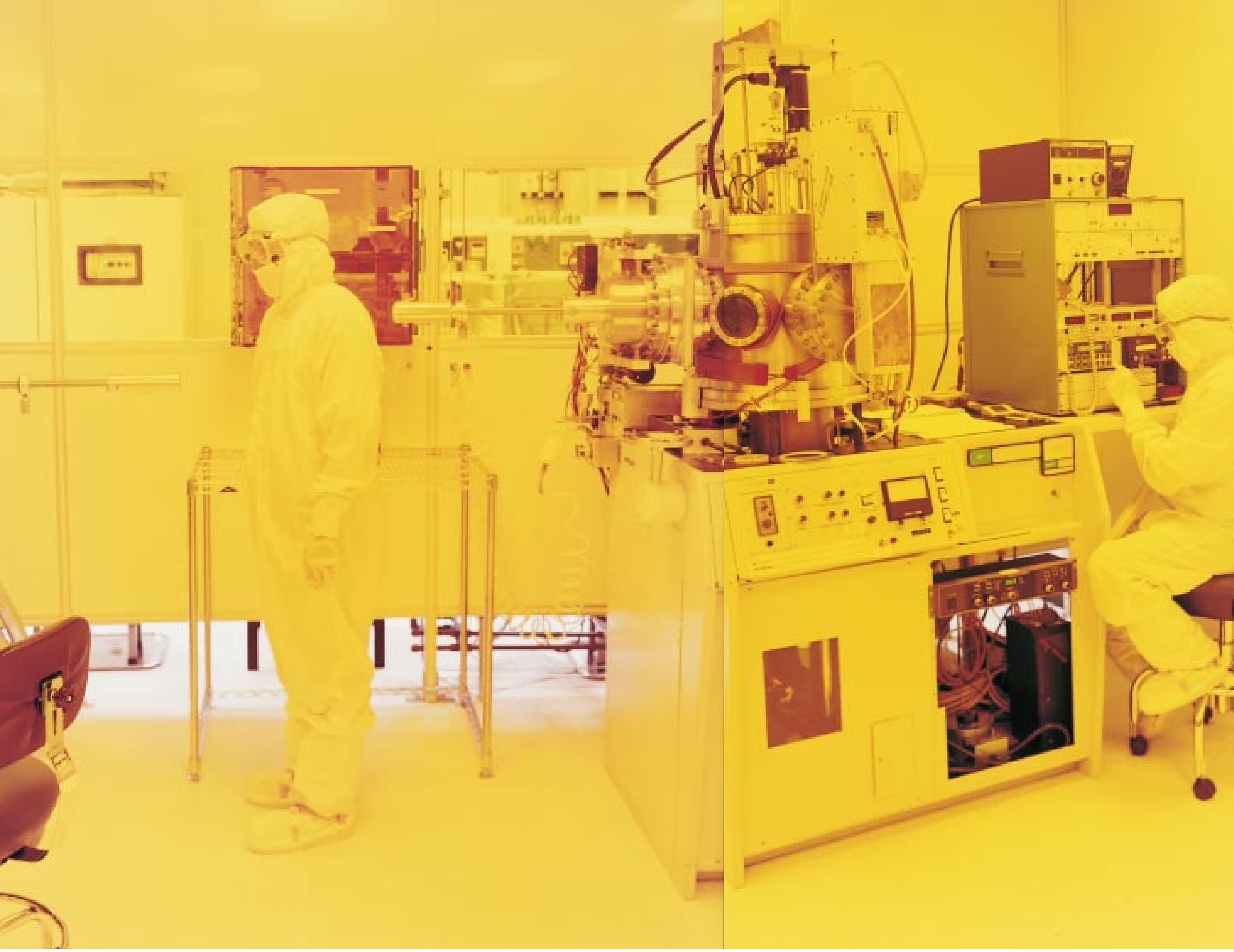
Photographs by Olivier Laude

TODAY'S FASTEST supercomputers run too slowly to do tomorrow's science. Despite the ongoing revolution in communications and information processing, many computational challenges critical to the future health, welfare, security and prosperity of humankind cannot be met by even the quickest computers. Crucial advances in pivotal fields such as climatology, medicine, bioscience, controlled fusion, national defense, nanotechnology, advanced engineering and commerce depend on the development of machines that will operate at speeds at least 1,000 times faster than today's biggest supercomputers [see "Crucial Tasks for Hypercomputers," on page 41].

Solutions to these incredibly complex problems hinge on the ability to simulate and model their behavior with a high degree of fidelity and reliability, often over long periods. This level of performance goes far beyond that of present-day supercomputers, which at best can execute several trillion floating-point operations per second (teraflops). It could take 100 years, for example, for the largest existing system to perform a complete protein-folding computation—a long-sought capability. To accomplish this kind of analysis task, researchers need hypercomputing systems that achieve at least petaflops speeds—that is, more than a quadrillion floating-point operations (arithmetical calculations) per second.

Not only do current high-end computers run too slowly, they cost too much. The three-teraflops (peak performance) ASCI (Accelerated Strategic Computer Initiative) Blue systems that are dedicated to the stewardship of the U.S. nuclear stockpile cost approximately $120 million each. That's equivalent to a price/performance factor of $40 per peak megaflops (million flops), which is more than 10 times greater than the price/performance of a premium personal computer. High-end computers impose indirect costs as well. Annual payments for

QUICK COMPUTER: The three-teraflops ASCI (Accelerated Strategic Computer Initiative) Blue system at Lawrence Livermore National Laboratory helps to maintain the nation's nuclear weapons stockpile.



FAST CHIPS: Engineers at TRW's Space Park facility in Redondo Beach, Calif., use sputtering machines to deposit thin superconducting films on silicon wafers as part of the fabrication of prototype superconducting processor chips.

the electrical power to operate such systems can easily exceed $1 million. Housing their oversize footprints can also add significant expense. Paying crack programmers to write the complex code for these machines is yet another cost.

Despite their impressive processing speeds, high-end systems do not make good use of the computing resources they have, resulting in surprisingly low efficiency levels. Twenty-five percent efficiency is not uncommon, and efficiencies have dropped as low as 1 percent when addressing certain applications.

The hybrid technology multithreaded (HTMT) system is a new class of computer that offers 100 times the capability of present high-end machines for roughly the same cost, power usage and floor space. Further development could bring the technology beyond a quadrillion flops to trans-petaflops territory—1,000 times the performance of today's best systems or more. To achieve these goals, a multi-institutional, interdisciplinary team has created a computer architecture able to harness various advanced processing, memory and communications technologies, leveraging their strengths and complementing their limitations. The basic elements of HTMT have been developed with financial support from NASA, the National Security Agency, the National Science Foundation and the Defense Advanced Research Projects Agency; actual construction awaits further governmental funding.

Ironically, it is the very success of computing technology that reveals its limitations. Back in the late 1970s, personal computers could barely play Pong. A system capable of executing a major science problem of the day at a performance level of a few tens of megaflops could cost $40 million or more. In contrast, PCs now priced at less than $2,000 can outperform those machines.

Historically, the supercomputer industry has pushed the frontiers of processing performance with a combination of advanced technology and architectures customized to address specific problems. The unfortunate side effect has been high price tags. Exorbitant costs and lengthy development times have kept the market for such systems relatively flat while other segments of the computer industry have grown explosively. With these costs forcing up the price to the customer, the overall supercomputer market and corporate investment in the technology have remained limited, producing a classic commercial death spiral.

Even when alternative approaches have been tried—including custom vector computer architectures (which efficiently perform a single operation on a list of numbers using pipelined memory access and arithmetic functional units) as well as massively parallel systems integrating large arrays of cooperating microprocessors—the costs of such systems have remained high while operational efficiencies for many applications have suffered. In the past two or three years, a number of groups have built highly parallel general-purpose computers with peak performance levels of more than a teraflops. Yet low efficiency levels mean that little of this processing capability can be brought to bear on real-world applications. As a result, commodity clusters—networked arrays of standard computing subsystems—are perceived as the only economically viable pathway: they require little additional development in spite of the programming difficulties and communications delays inherent in using clustered systems.

Research on new classes of petaflops-capable systems has been under way since the mid-1990s. Engineers have been attacking the speed problem on all fronts, pursuing various technology paths to such machines. With sufficient R&D support, all can be accomplished within this decade [see "Five Routes to Ultrafast Processing," on the next page]. Although each method has its strengths and weaknesses, one of the most widely applicable is the HTMT design.

HTMT exploits a diverse array of advanced technologies within a single flexible and optimized system. The project attempts to achieve efficient trans-petaflops performance by incorporating superfast processors, high-capacity communications links, high-density memory storage and other soon-to-mature technologies in a dynamic, adaptive architecture.

No matter what course they take, designers of trans-petaflops systems all face three challenges. First, they must find a way to aggregate sufficient processing, memory and communications resources to achieve the targeted peak-computing capabilities despite practical constraints of size, cost and power. The second goal is to attain reasonable operational effi-

Crucial Tasks for Hypercomputers

Many intricate scientific problems with enormous social and political implications await solutions that can be processed only on computers that can execute more than a quadrillion floating-point operations per second—trans-petaflops performance.

Climate Modeling
Perhaps the most critical issue facing the earth's inhabitants is the need for accurate predictive scenarios for both short- and long-term weather changes. First, trans-petaflops computers could integrate the huge quantities of satellite data into detailed maps. The mapped data could then be used to simulate and model the chaotic and interrelated behaviors of the elements of our global climate system, allowing accurate predictions.

Controlled Fusion
Both an answer to the world's energy problems and a way to power spacecraft across the solar system, thermonuclear fusion's vast complexity has kept it continually just over the horizon. Trans-petaflops computers would simulate the thermal, electromagnetic and nuclear interactions of large numbers of particles in a dynamic magnetic medium to help in designing practical fusion reactors.

Medicine/Bioscience
Considerably faster computing capability could give medicine the edge in combating continuously evolving diseases. This job requires molecular-level analysis to achieve nearly instantaneous drug design, including exploring complex protein folding.

Agriculture
To feed the earth's ever growing population, rapid computation will help develop new genetically engineered crops and solve the complex problems involved in managing the world's ecology.

National Defense
With the real-world testing of nuclear weapons banned, trans-petaflops machines could model the behavior of these systems to help maintain the readiness of the strategic weapons stockpile. Real-time decryption of increasingly complicated secret codes is one key to maintaining national defense.

Commerce and Finance
Large-scale mining of the enormous data spaces containing business information and economic statistics will allow a more accurate simulation of commercial systems.

Nanotechnology
With digital electronics shrinking to the atomic scale, where quantum mechanics is important, chip designers can no longer model electronics using averaged physical parameters.

Advanced Engineering
Ultrafast processing will be needed to simulate the behavior of new materials and composites at the microscale. Future aircraft design and that of other complex engineered systems will benefit from the same type of detailed modeling capabilities.

Astronomy
To model the galaxy and its 100 billion stars properly, new, superfast computers will be required to analyze the complex interplay of the interstellar medium and heavier molecules.

ciencies in the face of standard degradation factors. These include latencies (time delays) across the system, contention for shared resources such as common memory and communications channels, overhead-related resource reductions caused by the need to manage and coordinate concurrent tasks and parallel resources, and wastage of computing resources (starvation) caused by insufficient task parallelism or inadequate load balancing. The third objective concerns finding ways to improve the usability of the system—a somewhat arbitrary measure comprising the issues of generality (general utility), programmability and availability.

Superconducting Processors

DURING THE PAST DECADE, digital logic has been dominated by CMOS (complementary metal oxide semiconductor) processors. CMOS technology has provided lower power and greater performance while system densities have increased at an exponential rate. Yet the fastest digital logic technology on earth is not CMOS. An altogether different technology using another kind of physics claims that title: superconducting logic.

Discovered at the beginning of the 20th century, superconductivity is the ability to conduct electricity with no resistance, a phenomenon that some materials exhibit when cooled to cryogenic temperatures. In principle, a loop of superconducting wire can sustain an electric current forever. More important, superconducting devices exhibit quantum-mechanical behavior in macroscale electronic components and circuits. In the early 1960s researchers developed a nonlinear switching device based on superconductivity called the Josephson junction, which was found to have exceptional speeds.

The HTMT hypercomputer design will employ high-speed superconducting logic processors based on Josephson junction technology. In rapid single-flux quantum (RSFQ) technology, supercon-

Five Routes to Ultrafast Processing

One approach to attaining trans-petaflops computing performance (more than a quadrillion floating-point operations per second) is to use a hybrid architecture combining several soon-to-be-available advanced technologies (*see accompanying article*). Here are five other technical pathways to achieving that goal.

NAME	METHOD	EXAMPLE	BEST APPLICATIONS
1 SPECIAL-PURPOSE ARCHITECTURE OR SYSTOLIC ARRAY	Specially designed hardware and software that mirror the abstract problem to be solved. Runs in parallel with a fast data pipeline to speed computation	Grape Project (University of Tokyo)	Huge multibody calculations, stellar cluster simulation, bioinformatics
2 CELLULAR AUTOMATA	Finite-state machine in which many relatively simple computing cells in a large 2-D or 3-D matrix operate in lockstep during each clock cycle. Each cell's actions depend on its internal state and those of its nearest neighbors	Never fully executed	Computational fluid dynamics, diffusion simulations
3 PROCESSOR-IN-MEMORY (PIM) ARCHITECTURE	With a good deal of processing and memory on each chip, the system logic sees all the bits coming out of the dynamic random-access memory (DRAM) at the same time. There's lots of memory access and little delay in data transmission speed processing during each cycle	IRAM (University of California at Berkeley) Blue Gene (IBM)	Image processing, data encryption, rapid database searches, protein-folding modeling
4 BEOWULF OR CLUSTER ARCHITECTURES	A high-bandwidth mesh system interconnects many low-cost, commodity processors (each a partial-system-on-a-chip device) in a high-density array	GigAssembler software (International Human Genome Sequencing Consortium)	Wide range of problems; deciphering the human genome
5 DISTRIBUTED COMPUTING OR MEGACOMPUTING ARCHITECTURES	Harness the unused computing cycles on the estimated 500 million personal computers linked to the Internet. Inefficient communications is a drawback	SETI@home (Serendip Project)	Huge parallel problems such as Monte Carlo simulations and monitoring the function of the Internet

Not only do current HIGH-END SUPERCOMPUTERS run too slowly, they COST TOO MUCH and use too much power.

ducting loops store information as tiny magnetic flux quanta (by discrete current levels). The loops, called superconducting quantum interference devices, or SQUIDs, are simple mechanisms originally developed as sensing devices that comprise two Josephson junctions connected by an inductor, which is like a solenoid. With both Josephson junctions operating, a current injected into the loop will continue indefinitely. SQUIDs exhibit the interesting characteristic of having distinct states of operation: they may contain no current, sustain the basic current, or have a current that is some integral multiple times the basic current but nothing in between. This remarkable property results from quantum-mechanical effects. To represent the 0's and 1's of digital code, RSFQ logic gates use discrete currents (or fluxes) rather than distinct voltage levels. When cooled to a temperature of four kelvins, these units can operate at more than 770 gigahertz, the fastest (single-gate) processing speeds ever achieved and approximately 100 times quicker than conventional CMOS logic.

RSFQ technology will allow the hybrid computing system to run nominally at from 100 to 200 gigaflops (billion flops) per processor as opposed to a few gigaflops, as in standard CMOS processors. In addition, the minuscule and packetized nature of magnetic flux quanta in RSFQ devices cuts crosstalk and power consumption by a couple of orders of magnitude. This rapidly maturing technology reduces parallelism requirements, cost, power demand and system size.

Boosting Efficiency

WITH SUPERFAST processors in place, HTMT seeks to make efficient use of their powerful capabilities. Those processors should spend their time doing little else but computations. Conventional approaches such as commodity clusters require large-scale tasks to be run on similarly large-scale computational nodes. Often a computational node on a conventional system must wait while a remote request to another node is being serviced. Unless operators exactly balance the workload, some nodes will continue to compute while others, having finished their jobs, will stall. Even when engineers employ load-balancing software techniques, the overhead required for accomplishing this function can reduce efficiency.

Unlike any other computer architecture, HTMT revolutionizes the relation between the processing system and the memory system. In ordinary multiprocessor systems, the computational processors manage and manipulate the "dumb" memory system; in contrast, HTMT's "smart" memory system administers the processors. HTMT and other tightly coupled parallel computers consider the workload on the processing elements and make on-the-fly decisions as to which part of a task should be performed by what hardware. In doing so, the processors work out of their local registers and some high-speed buffer memories, thus avoiding having to reach too far out into the system. The result is a drop in latency problems. The processors do not spend time managing memory resources, which are just wasted processing cycles that add to overhead; these logistical decisions are made by the small low-cost processors in the memory.

The HTMT design attacks the problem of latency in two ways. First, the system employs a dynamic, adaptive resource management scheme based on a multithreaded architecture that enables HTMT to switch from one stream of instructions to another within a single cycle. Whereas most computers operate with one stream of instructions, HTMT will feature multiple instruction streams. By using overlapping communications, the processors can work on many outstanding requests simultaneously. Say a superconducting processor needs to load information from a cache or a high-speed buffer, a procedure that will take many 10-picosecond cycles. As this request is served by the memory system, the processor can switch to another data stream to find operations that can be performed immediately.

The second way HTMT will handle the latency issue is by employing processor-in-memory technology (PIM), wherein small secondary satellite or taxi logic processors are placed in its memory devices. A few years ago fabrication advances allowed CMOS logic and dynamic random-access memory (DRAM) cells to be put onto the same silicon die, permitting them to be closely integrated. These cheap devices deal with overhead—that is, they manipulate information in the memory, again allowing the superconducting processors to focus on computing. PIM processing technology can also handle memory-intensive functions such as data gathers—collecting needed information from various locations and placing it in one dense object—as well as carrying out the reverse operation of data scatters—distributing the information to the correct locations.

Although the technologies and architecture incorporated by the HTMT system may be innovative, the means of managing these resources and the computing discipline employed by HTMT are truly revolutionary. The system will use new percolation techniques in which the PIM processors decide when a new piece of work should be performed. They will determine when to migrate all information that needs to be executed up to rapid-access buffer memories near the high-speed superconducting processors.

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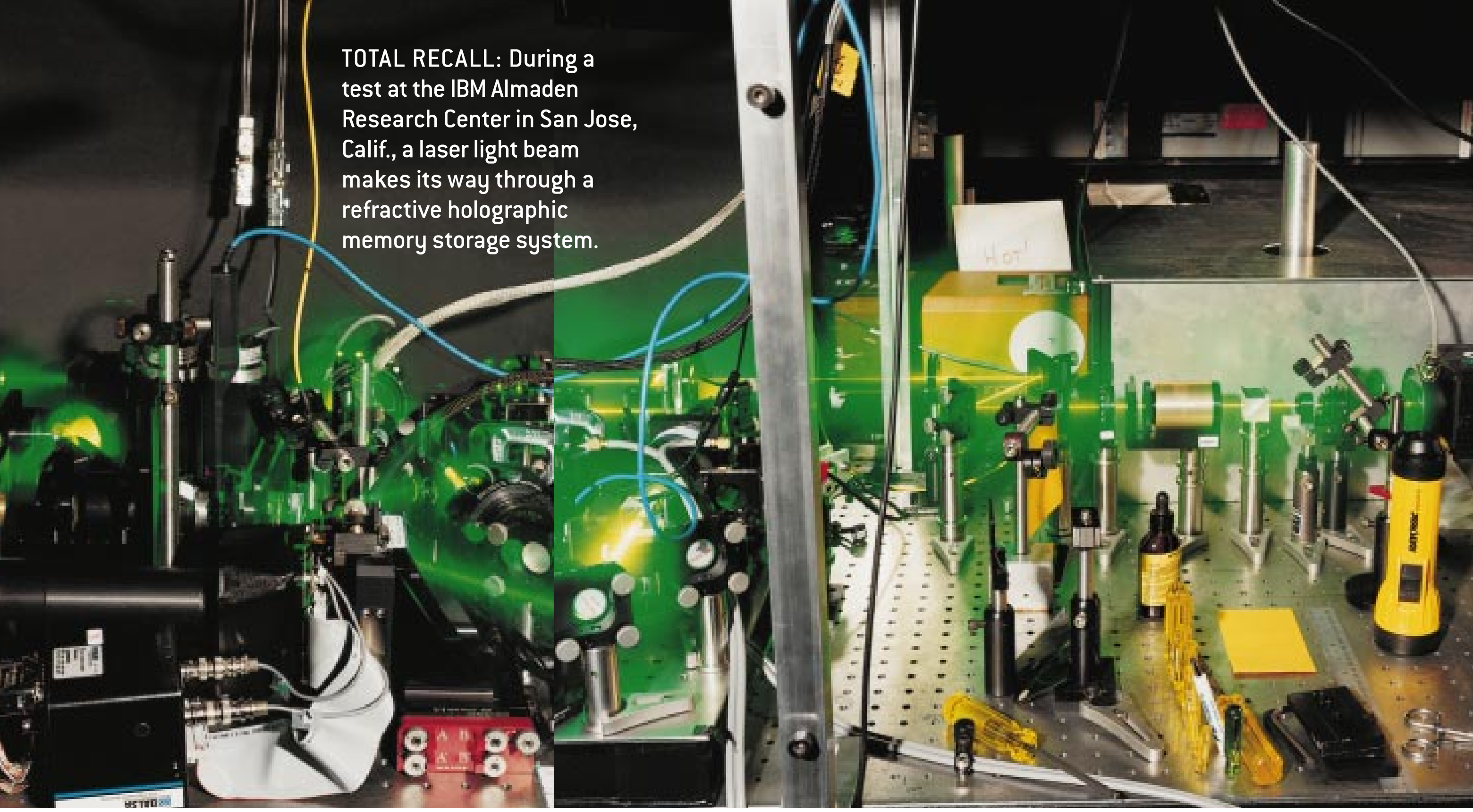

TOTAL RECALL: During a test at the IBM Almaden Research Center in San Jose, Calif., a laser light beam makes its way through a refractive holographic memory storage system.

For example, when a specific subroutine is required, it and the special information it needs to execute its function will be moved up to the processors. This proactive method of prestaging necessary information is a way to avoid creating long latency delays in connecting to the main memory. The technique also frees the high-speed processors from having to perform logistical overhead operations, because they are not needed to bring information to the processing sites.

Improving Usability

THE THIRD MAJOR challenge to trans-petaflops computing concerns the usability of the system: researchers must increase its generality (to ensure that it can handle a wide variety of problems), make it easier to program, and boost its availability, or uptime. HTMT addresses these issues in several ways.

By using a global name space in a shared-memory computing structure, every processor can "see" all of the memory. This method is more general than typical distributed- (or fragmented-) memory computing techniques because it provides efficient access by any processor to all data without having to engage software routines on a remote processor to assist in the data transfer. More actions can be performed simultaneously, speeding execution. In addition, by letting the system conduct dynamic rescheduling—responding to run-time information—it can perform certain computations more effectively, a capability that adds to its generality. And because this arrangement is closer to the way computational scientists think about their problems, programming the system is more intuitive. Typically programmers must determine beforehand how a problem should be handled by a system, a complex and laborious task. But an HTMT system makes many of these decisions by itself, thereby helping to alleviate one of the biggest difficulties in working with large computers—programming them.

The hybrid computing system will

Key Concepts/*Hypercomputing*

Contention—Time delay created when two processors try to access a shared resource simultaneously

Latency—Delay caused by the time it takes for a remote request to be serviced or for a message to travel between two processing nodes

Load Balancing—Distributing work evenly so that all processing nodes are kept occupied as the program is executed

Overhead—Time spent on noncomputational functions such as the logistical management of parallel resources and concurrent tasks

Percolation—Method of managing tasks and data movement without incurring delays caused by overhead, latency, contention or starvation

Processor-in-Memory (PIM)—Integrated circuits that contain both memory and logic on the same chip

Starvation—Wastage of computing resources caused by insufficient program parallelism or poor load balancing

Wave Division Multiplexing (WDM)—Method by which the effective bandwidth of an optical channel can be increased by using optical signals with different wavelengths

The hybrid computer REVOLUTIONIZES the relation between the PROCESSING system and the MEMORY system.

provide greater availability to users through the use of higher-capability subcomponents, allowing it to achieve the same level of performance with fewer parts. This parts reduction increases the mean time between failures of the entire system, thus boosting operational uptime.

Holographic Memory Storage

ANOTHER INNOVATIVE aspect of the HTMT system will be its use of high-density-capacity holographic memory storage devices. This alternative to the semiconductor-based DRAM is being explored by academic and industrial research laboratories and should provide superior storage density as well as lower power consumption and costs.

Holographic storage systems use light-sensitive materials to accumulate large blocks of data. Photorefractive and spectral hole–burning techniques represent two distinct approaches. In photorefractive storage, a plane of data modulates a laser beam (signal) that interferes with a reference beam in a small rectangular block of a storage material such as lithium niobate. The hologram results from the electro-optic effect that occurs when local electric fields are created by trapped, spatially distributed charge carriers excited by the interfering beams. Many data blocks may be stored in the same target material. They are differentiated by varying either the angle of incidence or the wavelength of the laser beam. The spectral hole–burning technique relies on a nonlinear response of a storage material to optical stimuli. Data are represented by changes in the photosensitive medium's absorption spectrum. Many bits can be stored at a given spatial location.

Photorefractive methods are more far advanced. But in the long-term, spectral hole–burning technology may yield significantly higher memory density. Typical holographic devices currently feature access times of several milliseconds—approximately the same as conventional secondary storage devices such as hard disks and CD-ROM drives. But advanced techniques employing tunable lasers or arrays of laser diodes each set at a slightly different angle to one another are expected to yield access times of a few tens of microseconds. Although these access times are about two orders of magnitude longer than that of DRAM, their data bandwidths are the same or greater, and the systems are about 100 times faster than conventional disk drives. Storage capacities of 10 gigabits or more in blocks as small as a few cubic centimeters are expected within the next decade.

Optical Communications

TO CONNECT THE SPEEDY superconducting processors and high-density holographic memory systems in a network, HTMT will use high-capacity optical data pipelines. Instead of employing electrons in metal wires, HTMT will speed communications by using photons in fiber-optic cables. Wires can easily handle hundreds of megabits per second, and speeds of a few gigabits per second (gbps) can be achieved by using differential pairs of input/output pins (one goes up while the other goes down). But it could take tens of millions of wires to supply all the global communications bandwidth required of systems operating in the petaflops regime. With modulated lasers, digital light signals can transmit at up to 10 gbps per channel or more in conventional optical communications systems.

Employing multiple wavelengths (or colors) of light carrying digital information dramatically improves fiber-optic bandwidth or channel capacity. HTMT will use an advanced optical transmission system called wave division multiplex (WDM) communications. It should provide about 100 times the per-channel bandwidth of the best conventional metal-wire communications systems. WDM allows separate digital signals, each with its own dedicated light wavelength, to travel together through the same channel. The number of different wavelengths that can be simultaneously transmitted through a single channel has grown to around 100 in recent years, and in time this figure may rise further. With improved receiver, transmitter and switch technology now in development, switching rates of 50 megahertz or more will soon be possible. Still experimental devices may bring about rates on the order of one gigahertz in the future. This capacity level would be sufficient to manage the huge information flow of a petaflops-scale computing system.

These next-generation hypercomputers would offer an important tool for exploring the world's most pressing problems, including global warming, disease epidemics and cleaner energy. In 1999 the President's Information Technology Advisory Committee strongly recommended financial support for these kinds of projects. Research groups have demonstrated that HTMT technologies could be the best route to trans-petaflops performance. Proper funding is all that is needed to put these systems in place. SA

This article is the first in a two-part series on next-generation supercomputers. The second part, "The Do-It-Yourself Supercomputer," will appear in the August issue.

MORE TO EXPLORE

Challenges of Future High-End Computing. David H. Bailey in *High Performance Computer Systems and Applications.* Edited by Jonathan Schaeffer. Kluwer Academic Publishers, 1998. Preprint available at **www.nersc.gov/~dhbailey/dhbpapers/future.pdf**

In Pursuit of a Quadrillion Operations per Second. Thomas Sterling in *NASA HPCC Insights,* No. 5; April 1998. Available at **www.hpcc.nasa.gov/insights/vol5/petaflop.htm**

The author's Web site: **www.cacr.caltech.edu/~tron/**

A Hybrid Technology Multithreaded (HTMT) Computer Architecture for Petaflops Computing. Thomas Sterling. On the JPL/NASA Project HTMT Web site at **http://htmt.jpl.nasa.gov/intro.html**

NASA high-performance computing and communications Web site: **www.hq.nasa.gov/hpcc/petaflops/**

The **Truth** and the **Hype** of HYPNOSIS

BY MICHAEL R. NASH

Photographs by Kyoko Hamada

Though often denigrated as fakery or wishful thinking, hypnosis has been shown to be a real phenomenon with a variety of therapeutic uses—especially in controlling pain

"You are getting sleepy. Verrry sleepy . . ."

A waistcoated man swings his pocket watch back and forth before the face of a young woman seated in a Victorian-era parlor. She fixes her gaze on the watch, tracking its pendular motion with her eyes. Moments later she is slumped in her chair, eyes closed, answering the hypnotist's questions in a zombielike monotone.

Everyone has seen a depiction of hypnosis similar to this one in movies and on television. Indeed, say the word "hypnosis," and many people immediately think of pocket watches. But it is now much more common for hypnotists simply to ask a subject to stare at a small, stationary object—such as a colored thumbtack on the wall—during the "induction patter," which usually consists of soothing words about relaxation and suggestions to concentrate.

But is hypnosis a real phenomenon? If so, what is it useful for? Over the past few years, researchers have found that hypnotized individuals actively respond to suggestions even though they sometimes perceive the dramatic changes in thought and behavior they experience as happening "by themselves." During hypnosis, it is as though the brain temporarily suspends its attempts to authenticate incoming sensory information. Some people are more hypnotizable than others, although scientists still don't know why. Nevertheless, hypnosis is finding medical uses in controlling chronic pain, in countering anxiety and even—in combination with conventional operating-room procedures—in helping patients to recover more quickly from outpatient surgery.

Only in the past 40 years have scientists been equipped with instruments and methods for discerning the facts of hypnosis from exaggerated claims. But the study of hypnotic phenomena is now squarely in the domain of normal cognitive science, with papers on hypnosis published in some of the most selective scientific and medical journals. Of course, spectacles such as "stage hypnosis" for entertainment purposes have not disappeared. But the new findings reveal how, when used properly, the power of hypnotic suggestion can alter cognitive processes as diverse as memory and pain perception.

Wheat from the Chaff

TO STUDY any phenomenon properly, researchers must first have a way to measure it. In the case of hypnosis, that yardstick is the Stanford Hypnotic Susceptibility Scales. The Stanford scales, as they are often called, were devised in the late 1950s by Stanford University psychologists André M. Weitzenhoffer and Ernest R. Hilgard and are still used today to determine the extent to which a subject responds to hypnosis. One version of the Stanford scales, for instance, consists of a series of 12 activities—such as holding one's arm outstretched or sniffing the contents of a bottle—that test the depth of the hypnotic state. In the first instance, individuals are told that they are holding a very heavy ball, and they are scored as "passing" that suggestion if their arm sags under the imagined weight. In the second case, subjects are told that they have no sense of smell, and then a vial of ammonia is waved under their nose. If they have no reaction, they are deemed very responsive to hypnosis; if they grimace and recoil, they are not.

Scoring on the Stanford scales ranges from 0, for individuals who do not respond to any of the hypnotic suggestions, to 12, for those who pass all of them. Most people score in the middle range (between 5 and 7); 95 percent of the population receives a score of at least 1.

What Hypnosis Is

BASED ON STUDIES using the Stanford scales, researchers with very different theoretical perspectives now agree on several fundamental principles of hypnosis. The first is that a person's ability to respond to hypnosis is remarkably stable during adulthood. In perhaps the most compelling illustration of this tenet, a study showed that when retested, Hilgard's original subjects had roughly the same scores on the Stanford scales as they did 10, 15 or 25 years earlier. Studies have shown that an individual's Stanford score remains as consistent over time as

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his or her IQ score—if not more so. In addition, evidence indicates that hypnotic responsiveness may have a hereditary component: identical twins are more likely than same-sex fraternal twins to have similar Stanford scores.

A person's responsiveness to hypnosis also remains fairly consistent regardless of the characteristics of the hypnotist: the practitioner's gender, age and experience have little or no effect on a subject's ability to be hypnotized. Similarly, the success of hypnosis does not depend on whether a subject is highly motivated or especially willing. A very responsive subject will become hypnotized under a variety of experimental conditions and therapeutic settings, whereas a less susceptible person will not, despite his or her sincere efforts. (Negative attitudes and expectations can, however, interfere with hypnosis.)

Several studies have also shown that hypnotizability is unrelated to personality characteristics such as gullibility, hysteria, psychopathology, trust, aggressiveness, submissiveness, imagination or social compliance. The trait has, however, been linked tantalizingly with an individual's ability to become absorbed in activities such as reading, listening to music or daydreaming.

IT DOESN'T TAKE MUCH to induce hypnosis: staring fixedly at a spot on the wall and listening to the soothing voice of a hypnotist will do the trick for most people.

Under hypnosis, subjects do not behave as passive automatons but instead are active problem solvers who incorporate their moral and cultural ideas into their behavior while remaining exquisitely responsive to the expectations expressed by the experimenter. Nevertheless, the subject does not experience hypnotically suggested behavior as something that is actively achieved. To the contrary, it is typically deemed as effortless—as something that just happens. People who have been hypnotized often say things like "My hand became heavy and moved down by itself" or "Suddenly I found myself feeling no pain."

Many researchers now believe that these types of disconnections are at the heart of hypnosis. In response to suggestion, subjects make movements without conscious intent, fail to detect exceedingly painful stimulation or temporarily forget a familiar fact. Of course, these kinds of things also happen outside hypnosis—occasionally in day-to-day life and more dramatically in certain psychiatric and neurological disorders.

Using hypnosis, scientists have temporarily created hallucinations, compulsions, certain types of memory loss, false memories, and delusions in the laboratory so that these phenomena can be studied in a controlled environment.

What Hypnosis Isn't

AS SCIENTISTS DISCOVER more about hypnosis, they are also uncovering evidence that counters some of the skepticism about the technique. One such objection is that hypnosis is simply a matter of having an especially vivid imagination. In fact, this does not seem to be the case. Many imaginative people are not good hypnotic subjects, and no relation between the two abilities has surfaced.

The imagination charge stems from the fact that many people who are hypnotizable can be led to experience compellingly realistic auditory and visual hallucinations. But an elegant study using positron emission tomography (PET), which indirectly measures metabolism, has shown that different regions of the brain are activated when a subject is asked to imagine a sound than when he or she is hallucinating under hypnosis.

In 1998 Henry Szechtman of McMaster University in Ontario and his co-workers used PET to image the brain activity of hypnotized subjects who were invited to imagine a scenario and who then experienced a hallucination. The researchers noted that an auditory hallucination and the act of imagining a sound are both self-generated and that, like real hearing, a hallucination is experienced as coming from an external source. By monitoring regional blood flow in areas activated during both hearing and auditory hallucination but not during simple imagining, the investigators sought to determine where in the brain a hallucinated sound is mistakenly "tagged" as authentic and originating in the outside world.

Szechtman and his colleagues imaged the brain activity of eight very hypnotizable subjects who had been prescreened for their ability to hallucinate under hypnosis. During the session, the subjects were under hypnosis and lay in the PET scanner with their eyes covered. Their brain activity was monitored under four conditions: at rest; while hearing an audiotape of a voice saying, "The man did not speak often, but when he did, it was worth hearing what he had to say"; while imagining hearing the voice again; and during the auditory hallucination they experienced after being told that the tape was playing once more, although it was not.

The tests showed that a region of the brain called the right anterior cingulate cortex was just as active while the volunteers were hallucinating as it was while they were actually hearing the stimulus. In contrast, that brain area was not active while the subjects were imagining that they heard the stimulus. Somehow hypnosis had tricked this area of the brain into registering the hallucinated voice as real.

Another objection raised by critics of hypnosis concerns its ability to blunt pain. Skeptics have argued that this effect results from either simple relaxation or a placebo response. But a number of experiments have ruled out these explanations. In a classic 1969 report, Thomas H. McGlashan and his colleagues at the University of Pennsylvania found that for poorly hypnotizable people, hypnosis was as effective in reducing pain as a sugar pill that the subjects had been told was a powerful painkiller. But highly hypnotizable subjects benefited three times more from hypnosis than from the placebo. In another study, in 1976, Hilgard and Stanford colleague Éva I. Bányai observed that subjects who were vigorously riding stationary bicycles were just as responsive to hypnotic suggestions as when they were hypnotized in a relaxing setting.

In 1997 Pierre Rainville of the University of Montreal and his colleagues set out to determine which brain structures are involved in pain relief during hypnosis. They attempted to locate the brain structures associated with the suffering component of pain, as distinct from its sensory aspects. Using PET, the scientists found that hypnosis reduced the activity of the anterior cingulate cortex—an area known to be involved in pain—but did not affect the activity of the somatosensory cortex, where the sensations of pain are processed.

Despite these findings, however, the mechanisms underlying hypnotic pain relief are still poorly understood. The model favored by most researchers is that the analgesic effect of hypnosis occurs in higher brain centers than those involved in registering the painful sensation. This would account for the fact that most autonomic responses that routinely accompany pain—such as increased heart rate—are relatively unaffected by hypnotic suggestions of analgesia.

But couldn't people merely be faking that they had been hypnotized? Two key studies have put such suspicions to rest.

In a cunning 1971 experiment dubbed The Disappearing Hypnotist, Frederick Evans and Martin T. Orne of the University of Pennsylvania compared the reactions of two groups of subjects: one made up of people they knew to be truly hypnotizable and another of individuals they told to pretend to be hypnotized. An experimenter who did not know which group was which conducted a routine hypnotic procedure that was suddenly interrupted by a bogus power failure. When the experimenter left the room to investigate the situation, the pretending subjects immediately stopped faking: they opened

PEOPLE UNDER HYPNOSIS, **though deeply relaxed, can carry out the instructions of their hypnotist. This woman is being told that her arm is becoming as heavy as lead. Highly hypnotizable subjects will lower their arms under the imagined weight.**

their eyes, looked around the room and in all respects dropped the pretense. The real hypnotic subjects, however, slowly and with some difficulty terminated hypnosis by themselves.

Fakers also tend to overplay their role. When subjects are given suggestions to forget certain aspects of the hypnosis session, their claims not to remember are sometimes suspiciously pervasive and absolute, for instance, or they report odd experiences that are rarely, if ever, recounted by real subjects. Taru Kinnunen, Harold S. Zamansky and their co-workers at Northeastern University have exposed fakers using traditional lie-detector tests. They have found that when real hypnotic subjects answer questions under hypnosis, their physiological reactions generally meet the criteria for truthfulness, whereas those of simulators do not.

Hypnosis and Memory

PERHAPS NOWHERE has hypnosis engendered more controversy than over the issue of "recovered" memory. Cognitive science has established that people are fairly adept at discerning whether an event actually occurred or whether they only imagined it. But under some circumstances, we falter. We can come to believe (or can be led to believe) that something happened to us when, in fact, it did not. One of the key cues humans appear to use in making the distinction between reality and imagination is the experience of effort. Apparently, at the time of encoding a memory, a "tag" cues us as to the amount of effort we expended: if the event is tagged as having involved a good deal of mental effort on our part, we tend to interpret it as something we imagined. If it is tagged as having involved relatively little mental effort, we tend to interpret it as something that actually happened to us. Given that the calling card of hypnosis is precisely the feeling of effortlessness, we can see why hypnotized people can so easily mistake an imagined past event for something that happened long ago. Hence, something that is merely imagined can become ingrained as an episode in our life story.

A host of studies verify this effect. Readily hypnotized subjects, for instance, can routinely be led to produce detailed and dramatic accounts of their first few

WHAT DO YOU KNOW ABOUT HYPNOSIS?

IF YOU THINK ...	THE REALITY IS ...
It's all a matter of having a good imagination.	Ability to imagine vividly is unrelated to hypnotizability.
Relaxation is an important feature of hypnosis.	It's not. Hypnosis has been induced during vigorous exercise.
It's mostly just compliance.	Many highly motivated subjects fail to experience hypnosis.
It's a matter of willful faking.	Physiological responses indicate that hypnotized subjects are not lying.
It is dangerous.	Standard hypnotic procedures are no more distressing than lectures.
It has something to do with a sleeplike state.	It does not. Hypnotized subjects are fully awake.
Responding to hypnosis is like responding to a placebo.	Placebo responsiveness and hypnotizability are not correlated.
People with certain types of personalities are likely to be hypnotizable.	There are no substantial correlates with personality measures.
People who are hypnotized lose control of themselves.	Subjects are perfectly capable of saying no or terminating hypnosis.
Hypnosis can enable people to "relive" the past.	Age-regressed adults behave like adults playacting as children.
A person's responsiveness to hypnosis depends on the technique used and who administers it.	Neither is important under laboratory conditions. It is the subject's capacity that is important.
When hypnotized, people can remember more accurately.	Hypnosis may actually muddle the distinction between memory and fantasy and may artificially inflate confidence.
Hypnotized people can be led to do acts that conflict with their values.	Hypnotized subjects fully adhere to their usual moral standards.
Hypnotized people do not remember what happened during the session.	Posthypnotic amnesia does not occur spontaneously.
Hypnosis can enable people to perform otherwise impossible feats of strength, endurance, learning and sensory acuity.	Performance following hypnotic suggestions for increased muscle strength, learning and sensory acuity does not exceed what can be accomplished by motivated subjects outside hypnosis.

SCIENTIFIC AMERICAN Gets Hypnotized

Our staff sees what it's like to "go under"

Here at SCIENTIFIC AMERICAN we pride ourselves on our skepticism toward pseudoscience and on our hard-nosed insistence on solid research. So when we invited Michael R. Nash of the University of Tennessee at Knoxville to write the accompanying article on the scientific basis of hypnosis, we warned him that we'd put him through the wringer—which we did. But while editing the article, we began to wonder: Isn't this something we should experience ourselves? How many of us would be hypnotizable?

We invited Nash and research psychologist Grant Benham to New York so we could see what hypnosis was like firsthand. Six editorial staffers—three men and three women, none of whom had been hypnotized before—were willing to give it a try. What we found surprised us.

Nash and Benham set up two quiet offices for our initiation into hypnosis. Each researcher hypnotized three people individually, spending about an hour with each subject. They took us through the Stanford Hypnotic Susceptibility Scales, which rate an individual's responsiveness from 0 to 12.

One of the most surprising things about our hypnotic experience was its very banality. To induce hypnosis, Nash and Benham merely asked us to stare at a yellow Post-It note on the wall and spoke to us in a calm voice about how relaxed we were becoming and how our eyes were growing tired. "Your whole body feels heavy—heavier and heavier," they read from the Stanford script. "You are beginning to feel drowsy—drowsy and sleepy. More and more drowsy and sleepy while your eyelids become heavier and heavier, more and more tired and heavy." That soothing patter went on for roughly 15 minutes, after which all but one of us had closed his or her eyes without being directly told to do so.

The Stanford scales consist of 12 different activities ranging from trying to pull apart one's interlocked fingers and feeling one's elevated arm lower involuntarily to hallucinating that one hears a buzzing fly. Of the six of us, one scored an 8, one a 7, one a 6, two a 4 and one a 3. (A score of 0 to 4 is considered "low" hypnotizable; 5 to 7 is "medium" hypnotizable; 8 to 12 is "high" hypnotizable.) None of us accurately predicted how susceptible we would be: some who thought themselves very suggestible turned out to be poor subjects, and others who deemed themselves tough cases were surprised to find their two outstretched arms coming together by themselves or their mouth clamped shut so that they couldn't say their name.

We all had a sense of "watching" ourselves and were sometimes amused. "I knew what my name was, but I couldn't think how to move my mouth," recalled one staff member. Another said his fingers "felt stuck" during the finger-lock exercise. "At first they pulled apart easily enough, but then they seemed to sort of latch up. It was interesting to see that it was so difficult."

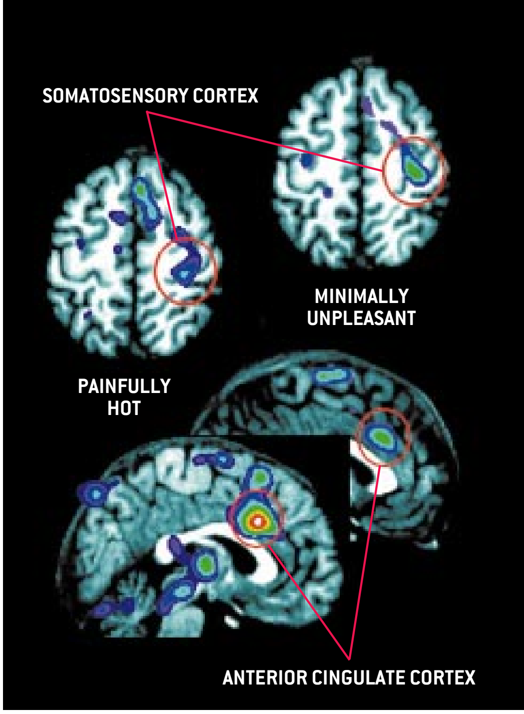
Only one of us experienced item number 12 on the Stanford scale—posthypnotic amnesia. In this exercise, the hypnotist tells the subject not to remember what occurred during the session. "Every time I'd try to remember," said the staff member who had this sensation, "the only thing that came back to me was that I shouldn't remember. But when Dr. Benham said it was okay to remember, it all came flooding back."

In general, the experience was much less eerie than we had expected. The feeling was akin to falling into a light doze after you've awakened in the morning but while you're still in bed. All of us found that we felt less hypnotized during some parts of the session than during others, as if we had come near the "surface" for a few moments and then slipped under again.

All in all, we concluded that seeing is believing when it comes to hypnosis. Or maybe we should say hearing is believing: I'm the one who heard—and swatted—the imaginary fly.

—*Carol Ezzell, staff writer and a 7 on the Stanford scales*

PEOPLE ARE AWARE of what they do during hypnosis, although their actions feel involuntary. Some of us laughed at our inability to say our names or open our eyes under hypnotic suggestion.



HYPNOSIS MIGHT ALLEVIATE pain by decreasing the activity of brain areas involved in the experience of suffering. Positron emission tomography (PET) scans of horizontal (*top*) and vertical (*bottom*) brain sections were taken while the hands of hypnotized volunteers were dunked into painfully hot water. The activity of the somatosensory cortex, which processes physical stimuli, did not differ whether a subject was given the hypnotic suggestion that the sensation would be painfully hot (*left*) or that it would be minimally unpleasant (*right*). In contrast, a part of the brain known to be involved in the suffering aspect of pain, the anterior cingulate cortex, was much less active when subjects were told that the pain would be minimally unpleasant (*bottom*).

PIERRE RAINVILLE ET AL., *SCIENCE*, VOL. 277, AUGUST 15, 1997

months of life even though those events did not in fact occur and even though adults simply do not have the capacity to remember early infancy. Similarly, when given suggestions to regress to childhood, highly hypnotizable subjects behave in a roughly childlike manner, are often quite emotional and may later insist that they were genuinely reliving childhood. But research confirms that these responses are in no way authentically childlike—not in speech, behavior, emotion, perception, vocabulary or thought patterns. These performances are no more childlike than those of adults playacting as children. In short, nothing about hypnosis enables a subject to transcend the fundamental nature and limitations of human memory. It does not allow someone to exhume memories that are decades old or to retrace or undo human development.

What It's Good For

SO WHAT ARE the medical benefits of hypnosis? A 1996 National Institutes of Health technology assessment panel judged hypnosis to be an effective intervention for alleviating pain from cancer and other chronic conditions. Voluminous clinical studies also indicate that hypnosis can reduce the acute pain experienced by patients undergoing burn-wound debridement, children enduring bone marrow aspirations and women in labor. A meta-analysis published in a recent special issue of the *International Journal of Clinical and Experimental Hypnosis,* for example, found that hypnotic suggestions relieved the pain of 75 percent of 933 subjects participating in 27 different experiments. The pain-relieving effect of hypnosis is often substantial, and in a few cases the degree of relief matches or exceeds that provided by morphine.

But the Society for Clinical and Experimental Hypnosis says that hypnosis cannot, and should not, stand alone as the sole medical or psychological intervention for any disorder. The reason is that anyone who can read a script with some degree of expression can learn how to hypnotize someone. An individual with a medical or psychological problem should first consult a qualified health care provider for a diagnosis. Such a practitioner is in the best position to decide with the patient whether hypnosis is indicated and, if it is, how it might be incorporated into the individual's treatment.

Hypnosis can boost the effectiveness of psychotherapy for some conditions. Another meta-analysis that examined the outcomes of people in 18 separate studies found that patients who received cognitive behavioral therapy plus hypnosis for disorders such as obesity, insomnia, anxiety and hypertension showed greater improvement than 70 percent of the patients who received psychotherapy alone. After publication of these findings, a task force of the American Psychological Association validated hypnosis as an adjunct procedure for the treatment of obesity. But the jury is still out on other disorders with a behavioral component. Drug addiction and alcoholism do not respond well to hypnosis, and the evidence for hypnosis as an aid in quitting smoking is equivocal.

That said, there is strong, but not yet definitive, evidence that hypnosis can be an effective component in the broader treatment of other conditions. Listed in rough order of tractability by hypnosis, these include a subgroup of asthmas; some dermatological disorders, including warts; irritable bowel syndrome; hemophilia; and nausea associated with chemotherapy. The mechanism by which hypnosis alleviates these disorders is unknown, and claims that hypnosis increases immune function in any clinically important way are at this time unsubstantiated.

More than 30 years ago Hilgard predicted that as knowledge about hypnosis becomes more widespread in the scientific community, a process of "domestication" will take place: researchers will use the technique more and more often as a routine tool to study other topics of interest, such as hallucination, pain and memory. He forecast that, thus grounded in science, the clinical use of hypnosis would simply become a matter of course for some patients with selected problems. Although we are not quite there today, hypnosis has nonetheless come a long way from the swinging pocket watch. SA

MORE TO EXPLORE

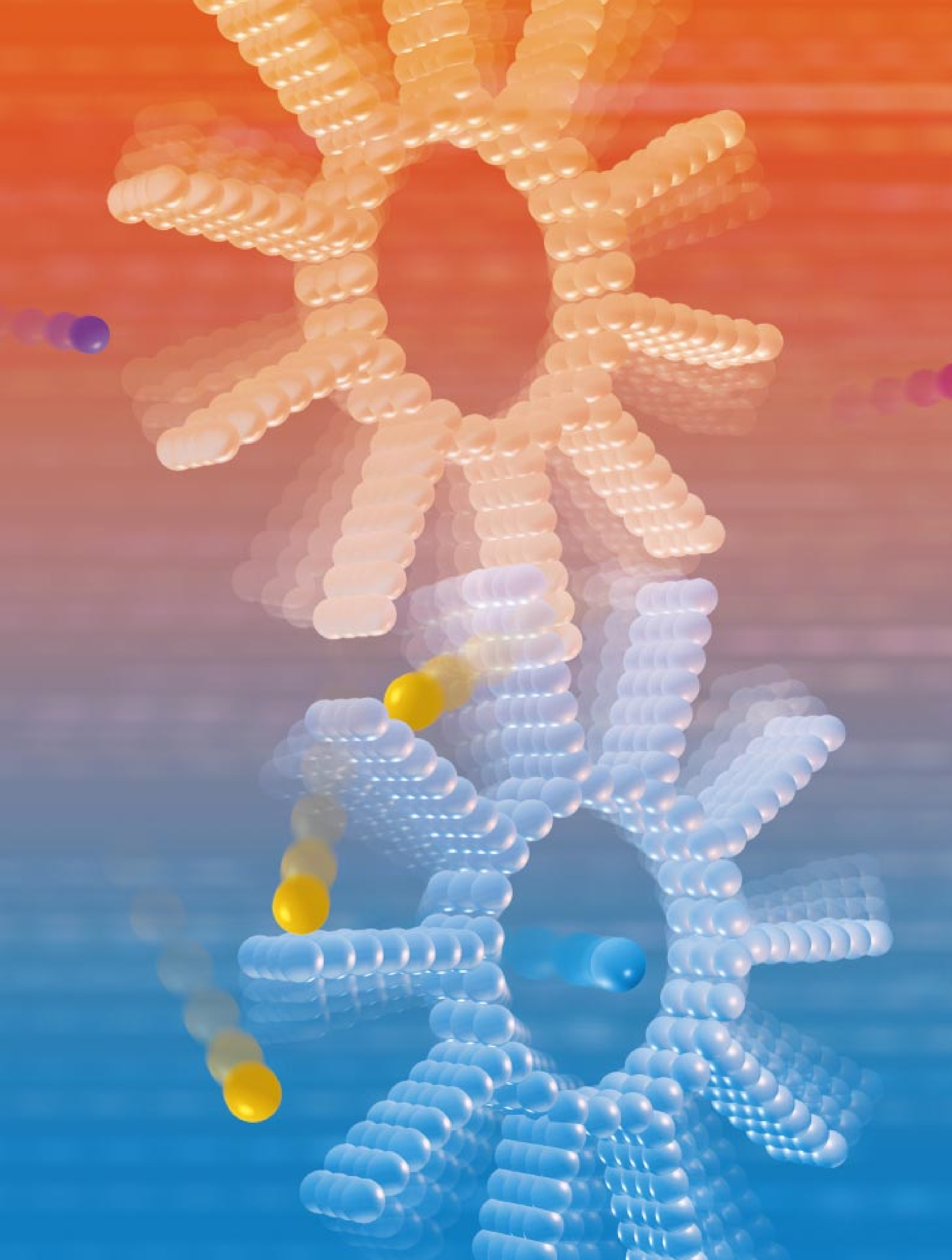
Hypnosis for the Seriously Curious. Kenneth Bowers. W. W. Norton, 1983.

Contemporary Hypnosis Research. Erika Fromm and Michael R. Nash. Guilford Press, 1992.

For an introduction to the history of hypnosis and its modern-day uses, visit the Web site of the Institute for the Study of Healthcare Organizations and Transactions at **www.institute-shot.com/hypnosis_and_health.htm**

For information on hypnosis research and clinical applications, visit the *International Journal of Clinical and Experimental Hypnosis* at **www.sunsite.utk.edu/IJCEH**

Video of an actual hypnosis session can be viewed at **www.sciam.com/2001/0701issue/0701nashbox1.html**



MAKING molecules INTO motors

Molecular turmoil, quantum craziness: microscopic machines must operate in a world gone mad. But if you can't beat the chaos, why not exploit it?

BY R. DEAN ASTUMIAN

HUDDLED IN THE RUINS OF a house in southwestern London, the protagonist of *The War of the Worlds* marveled at the strangeness of Martian technology:

> Of their appliances, perhaps nothing is more wonderful to a man than the curious fact that what is the dominant feature of almost all human devices in mechanism is absent—the *wheel* is absent.

An advanced technology can do away with things we regard as absolutely essential. Just that is happening now in a blossoming field at the intersection of physics, chemistry and biology: the study and construction of devices that serve as motors and pumps on the molecular scale. These mechanisms generally lack rotors, armatures and all the other trappings of conventional engines, but that is the least of their oddities. In an ordinary motor, energy is used to cause motion. In these motors, energy is used to cause a cessation of motion. Although they seem rather like an example of alien technology, they are the most common type of motor on our planet, the basis of the inner workings of all living cells.

Our physical intuition, formed by everyday observation of large machines, fails when we consider the world of the small. It is a capricious world, ruled by thermal and quantum fluctuations. For molecules, moving deterministically is like trying to walk in a hurricane: the forces propelling a particle along the desired path are puny in comparison to the random forces exerted by the environment. Yet cells thrive. They ferry materials, they pump ions, they build proteins, they move from here to there. They make order out of anarchy.

Over the past several years, researchers have finally begun to understand how. The basic insight, loosely described as the Brownian ratchet principle, is that random noise can be put to good use. The trick is to rectify the noise, to filter out the randomness you do not want so that you are left with what you do want. This principle resembles the phenomenon known as stochastic synchronization, whereby increasing the noise in a communications channel can actually make it easier to transmit a signal [see "The Benefits of Background Noise," by Frank Moss and Kurt Wiesenfeld; Scientific American, August 1995].

Using the techniques of chemistry, researchers have been designing miniature motors and devices that can manipulate molecules one at a time. These tiny machines imitate what protein motors and pumps do in living cells—convert chemical energy into mechanical work with almost 100 percent efficiency—and could carry out such tasks as molecular assembly, fine sifting, low-energy-consumption computation and semiconductor quality control. They may be the first step in turning the science fiction of nanotechnology, the dream of atom-by-atom control of matter, into science fact.

Braking into Motion

EVEN A FREAK HAILSTORM does not come close to the tempestuous bombardment that is routine in the molecular world, but the effects can be analogous. Usually when you park your car at the foot of a hill, turn off the engine and release the emergency brake, the car will not start climbing the hill. But imagine this scenario. Hundreds of hailstones strike the car every second, hitting all sides at random. Each one transfers a small amount of momentum to move the car a tiny distance forward or backward. On average, the momentum transferred to the car is zero, but in any time interval the car will move a little more in one direction than in the other.

You can take advantage of these random pushes in a very simple way. Put a brick behind the rear wheel to prevent the car from rolling backward and wait until a hailstone pushes it forward. If you do nothing, the car will soon roll back, but if you swiftly move the brick, you can trap the car in its new position. By continuing this process—moving the brick each time the car lurches forward—you can drive down the street, even up a hill.

It takes a keen eye and quick wit to move a brick under a heaving car in the middle of a violent hailstorm. Fortunately, the same effect can be achieved simply by replacing the standard brake with a ratchet—a device that allows motion in only one direction. A ratchet consists of a gear with asymmetric teeth and a pawl, a little arm that jams the gear and prevents it from turning backward. In a turnstile or ratchet wrench, the pawl is spring-loaded. Such a simple ratchet mechanism would keep the car moving forward. Progress would be agonizingly slow, however, because only a small fraction of the hailstones—those with enough momentum to overcome the force exerted on the ratchet by the spring—would have any effect.

A better alternative is to skew the teeth in the opposite direction and substitute the spring-loaded pawl with a piston activated by the brake pedal. When the brake is off, the piston is disengaged, and the car is free to lurch back and forth. When the driver pushes the brake pedal, the piston engages and locks the gear (and car) in place.

This modified ratchet does away with the need for careful measurement and intelligent intervention. All the driver has to do is sit in the car and pump the brake. Because of the skewed gear teeth, a few extra hailstones striking from behind are sufficient to move the car forward far enough to advance the gear by one tooth, whereas a larger number of hailstones from the front are necessary to push it backward by one tooth. This asymmetry ensures that the car moves forward even if the brake is engaged and disengaged randomly. The beauty of the system is that it requires no synchronization—none of the careful timing required in an ordinary engine.

Averaged over time, the hailstones exert no net force on the car. The vehicle acquires its forward motion from the application of the brake, which forces the piston down onto the gently sloping face of the lopsided teeth. Take away any component—the asymmetry of the ratchet teeth, the jittering caused by the hailstones or the external energy supplied by pumping the brake—and the mechanism would fail.

Needless to say, such a contrivance is quite unrealistic for a real car. A back-of-envelope calculation shows that a reasonable pumping rate could impart a velocity of no more than a kilometer per hour, about a tenth of the car's body length per second. The maximum force on the car would be one millionth the gravitational force, so at best the car could climb a very gradual slope.

But if the car is very small—say, the size of a large molecule—and immersed in water, the mechanism is much more effective [*see box on page 60*]. The mass

Overview / *Motors from Molecules*

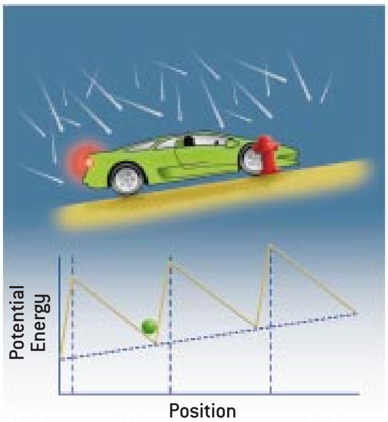
To make a molecular motor, it isn't enough just to make a miniature version of an ordinary motor. Researchers have had to rethink the very premises on which a motor operates.

- In ordinary motors, an energy input causes motion. In molecular motors, an energy input restrains motion. By selectively stopping the motions it doesn't want and letting through the ones it does—using a ratcheting mechanism akin to a ratchet wrench—the motor turns momentum from random environmental influences into organized motion.
- Ratchets sound like they get something for nothing, but the second law of thermodynamics wouldn't look kindly on that. Physicist Richard Feynman explained how these systems are completely kosher.
- Such motors make many of the dreams of nanotechnology possible. They also explain how living cells function amid the chaos of the microworld.

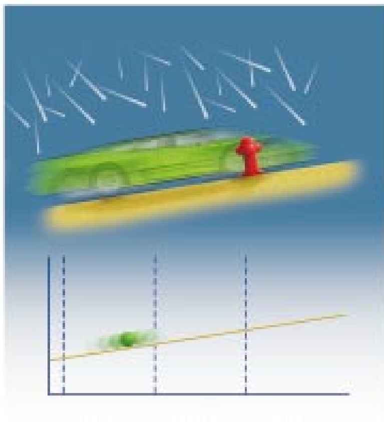
ILLUSTRATION ON PAGE 56: PHILIP HOWE

UPHILL BATTLE

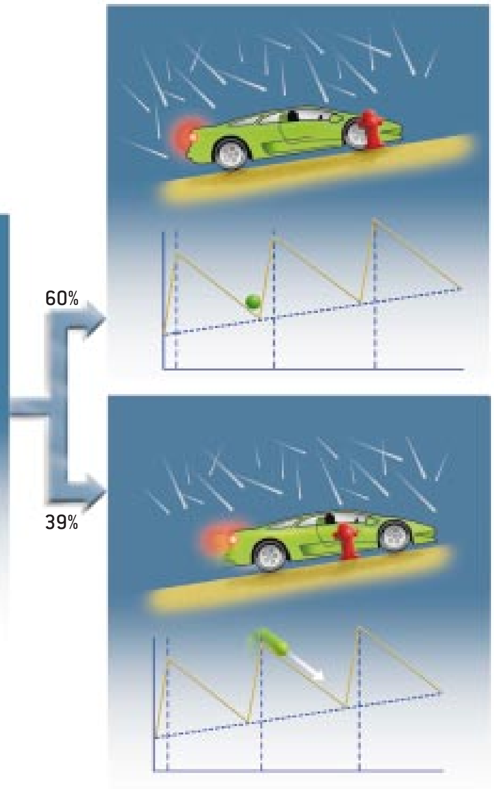
DRIVING UPHILL WITHOUT AN ENGINE is an apt metaphor for understanding molecular motors. It sounds impossible but can happen if a car is equipped with a special ratchet brake and is bombarded by hailstones. In terms of potential energy, the hill can be represented by a straight line and the brake (when applied) by a lopsided sawtooth.



When the brake is on, the car is forced down into the notch of the sawtooth. It is unlikely that a hailstone would push the car out of this locked position. (If one did, the car would actually tend to move backward—that is, the path of least resistance for the ratchet.)



When the brake is off, hailstones buffet the car, making it jiggle back and forth randomly. The probability of reaching a certain position can be calculated from the slope of the hill and the amount of time available. Despite the downhill bias, the car is more likely to move past the position of the peak to the right than the peak to the left (*dashed lines*).



Reapplying the brake pushes the car back to where it started (for this example, with 60% probability), forward one notch (39%) or back (1%; not shown).

ratio of a water molecule and a small protein is about the same as the mass ratio of a hailstone and a car. The difference is that water molecules hit the protein many billion times a second. These collisions produce the well-known jittering called Brownian motion. What is not so well known is that a Lilliputian ratchet could use Brownian motion to turn directionless energy into directed motion. A small protein could reach a velocity of one micron (more than 10 times its size) a second—the equivalent of 100 kilometers an hour for a car. The ratchet mechanism could overcome a force of up to 10 piconewtons, nearly a million times the force of gravity on a molecule.

It is amazing but true that two random processes can combine to produce a nonrandom effect. Physicist Juan M. R. Parrondo of Complutensian University in Madrid recently showed that the same principle applies to games of chance. Switching between two games, each a losing proposition, can turn the odds in your favor [*see box on page 62*].

Long Arm of the Second Law

A PHYSICIST'S FIRST reaction is that ratchets might break the second law of thermodynamics, whereby it is impossible to convert random thermal fluctuations into mechanical work. In his famous *Lectures on Physics,* Richard Feynman analyzed a ratchet attached to a paddle wheel. If the ratchet could prevent the wheel from going backward, molecular collisions would cause an irregular but relentless rotation of the wheel [*see illustration on page 61*]. The result: a perpetual-motion machine of the second kind—that is, one that defies the second law. (The device does not claim to manufacture energy out of nothing, so it does not violate the first law of thermodynamics, the law of conservation of energy.)

As Feynman showed, however, the device cannot work without an outside energy source. The pawl must be attached to the ratchet by a spring, which itself is

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PHILIP HOWE

vulnerable to thermal noise. Occasionally noise causes the spring to contract, lifting the pawl and prematurely disengaging the mechanism. Because of the asymmetry of the gear teeth, the ratchet will most likely slip back a notch. If the paddle wheel and pawl are at the same temperature, the tendencies to move forward (because of molecular collisions) and to move backward (because of the unreliable spring) exactly cancel. Despite superficial appearances, a ratchet system in thermal equilibrium will not rotate.

This restriction does not apply when the system is out of thermal equilibrium. If the paddle wheel is hotter than the spring, the ratchet rotates counterclockwise, as intuition would suggest. If the spring is hotter, the ratchet rotates clockwise—a motion that ratchets usually prevent. Any departure from equilibrium allows for ratchet-driven motion. Whatever creates the disequilibrium provides energy to the system. In the case of the car, the energy comes from the foot on the brake. The energy dissipates to heat as the car is forced into the locked position. In this way, these systems comply with the second law.

Although large thermal gradients are rare at the molecular level, other forms of disequilibrium are quite common. Three years ago organic chemist T. Ross Kelly and his colleagues at Boston College elaborated on this point with a clever experiment. They synthesized Feynman's ratchet from triptycene, a Y-shaped organic molecule that serves as the paddle wheel, and helicene, a G-shaped molecule that acts as the pawl and spring. Because the helicene has a bend in it, it is easier to turn the paddle wheel clockwise than counterclockwise. Despite this asymmetry, NMR spectroscopy showed that the frequencies of clockwise and counterclockwise turns were exactly equal, as Feynman predicted [see "Taming Maxwell's Demon," by George Musser; SCIENTIFIC AMERICAN, News and Analysis, February 1999].

Kelly's group then incorporated a nonequilibrium chemical process: the hydrolysis, or water-driven decomposition, of phosgene gas. A hydroxyalkyl group was attached to the pawl and an amino group to one vane of the paddle wheel. Together they served as a brake. Whenever the vane approached the pawl, the groups (primed by the phosgene) reacted and prevented any further counterclockwise rotation. The net effect was that most of the paddle wheels rotated clockwise. This system is not a true molecular motor—if the brake were released and reapplied, the wheel would tend to return to its starting point—but it does demonstrate the concept. Other groups have achieved continuous rotation using different ratchet mechanisms. A team headed by Ben L. Feringa of the University of Groningen, for instance, drives a molecular motor with light.

Pump the Brake

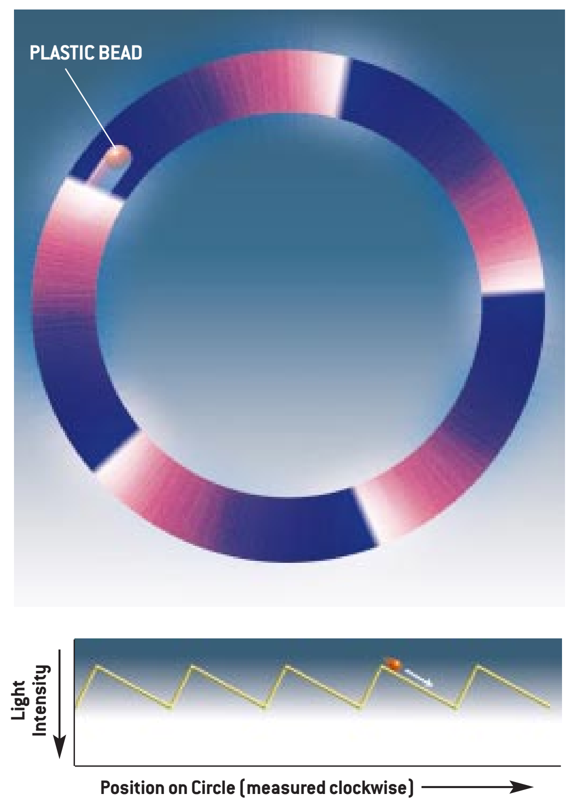
RECENT EXPERIMENTS suggest that at least some biological engines work by similar means. One example is the ion pump, a protein that pushes electrically charged particles through a cell membrane. Ions naturally flow from higher to lower

BRAKE LIGHT

BIZARRE THOUGH IT MAY SEEM, the brake-driven car is exactly analogous to a rudimentary molecular motor. In one elegant experiment seven years ago, Albert J. Libchaber, a physicist then at Princeton University, and his colleagues used a micron-size plastic bead floating in a beaker of water as the "car." They manipulated the bead using light beams; the subtle pressure of light refracted through the bead pushed it toward regions where the light intensity was strongest. One light beam created a circle of light that generally confined the bead: the "road." Superimposed on the road was a second beam that could be turned on or off: the "brake." The brake beam set up an alternating series of bright and dark regions, in which the positions of maximum and minimum intensity were not evenly spaced (*right*). Moving clockwise from a maximum, it was a short distance to the next minimum; moving counterclockwise, a long distance. This asymmetry is analogous to the skew of the gear teeth in a mechanical ratchet.

With the brake beam on, the bead moved in the direction of increasing intensity. On reaching the next maximum, it remained there as long as the brake was applied. With the brake beam off, the bead randomly lurched around the circle. If it managed to drift past a minimum, then reapplying the brake pushed it to the next maximum. Because of the asymmetry, the bead was more likely to move clockwise. The net velocity depended on how often the brake beam was turned on and off. As the frequency increased, so did the velocity, until it reached the point where Brownian motion could not keep up.

As with the car example, this system required no measurement, no choreography and no application of intelligence during operation. It worked even if the brake beam was turned on and off at random.



PHILIP HOWE

Unlike an ordinary engine, a Brownian motor REQUIRES NO MEASUREMENT and no choreography.

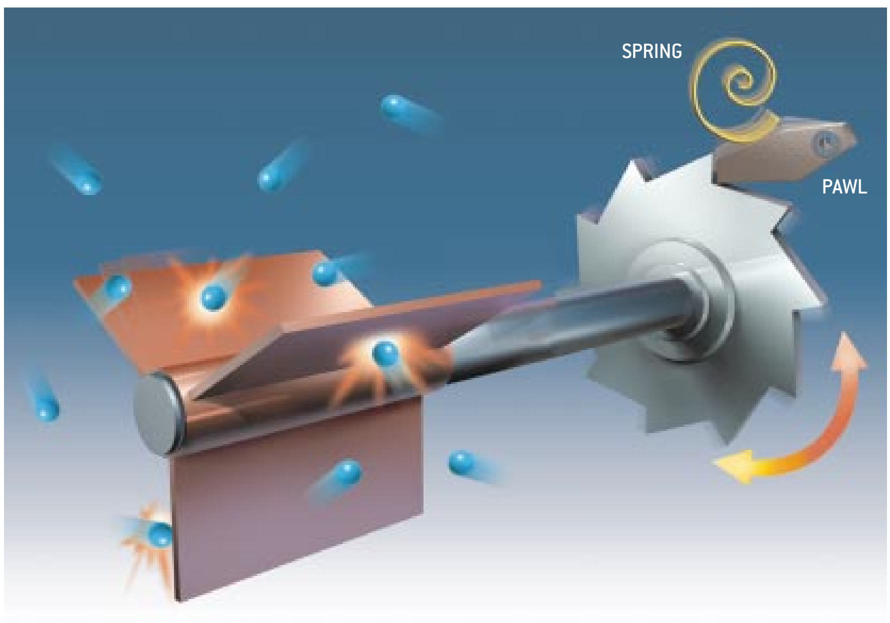
electrochemical potential, but these pumps can drive ions in the opposite direction, maintaining the electrochemical gradients essential for life.

The ion pump seems to be based on a simpler device, the ion channel. An ion channel is a biological rectifier: it allows electric current to flow in one direction only. A typical channel is a funnel-shaped protein about 10 nanometers long. Ions can move from the mouth of the funnel to the tip, but not the other way. Turning this rectifier into a pump requires some mechanism to modulate the size of the mouth and the strength of the interaction of an ion within the channel. The shape of the channel is well suited to this type of modification, because it acts like a lever: a small displacement of atoms near the tip of the funnel can result in a large change at the mouth. By making the mouth open and close cyclically, the pump can move ions from the tip of the funnel out the base—just as pumping the car brake caused the gear to turn in the opposite direction from what one would have expected.

The hydrolysis of adenosine triphosphate (ATP), the fuel used by cells, provides just the mechanism required to turn a channel into a pump. In a simplified description, the pump has two possible states. In the first state, the mouth is open to the inside of the cell and ions interact strongly with the interior of the channel. In the second, the mouth is closed to the inside and ions interact weakly with the interior. The binding of ATP favors the first state, and the release of the hydrolysis products favors the second. The process is analogous to the operation of a canal lock but with a crucial difference: it requires no control mechanism to synchronize the hydrolysis with the ion motion. It is enough to cycle randomly between two states of the protein. When the gate to the inside is open and the channel's energy level is low, an ion naturally enters the channel from the inside. When the gate to the inside is closed and the energy level is high, the ion flows to the outside. In the mid-1980s this ratchet picture was corroborated by Tian Y. Tsong, then at Johns Hopkins University, me, and our colleagues. We applied an alternating electric field to an ion pump and observed it driving ions up an electrochemical gradient, even without hydrolyzing ATP.

Another example is kinesin, a molecular forklift that transports proteins within the cell. Kinesin consists of two loosely attached domains and moves along a track called a microtubule, made of many individual molecules of the protein tubulin, each about 10 nanometers long. The electric potential between the kinesin and the microtubule usually has a sawtooth pattern, with energy barriers preventing the motion of kinesin from one tubulin molecule to the next. In the Brownian model, hydrolysis of an ATP molecule changes this potential to a flat shape and allows random collisions to jostle the kinesin. Release of the hydrolysis products returns the potential to the sawtooth shape, which, depending on how far the kinesin has drifted, can push the molecule forward.

This Brownian model of how kinesin moves differs radically from the traditional one, in which the shape of the molecule played the central role. The idea was that the two domains, acting like arms, let go of the microtubule one at a time and swing forward—as though they were moving along monkey bars in a playground. A clear prediction of this theory was that if one domain is removed, the resulting molecule should not be able to move along the microtubule. In 1998 Yasushi Okada and Nobutaka Hirokawa of the University of Tokyo replaced one of the domains with a charged loop of amino acids, so that the molecule had a different shape but nearly the same bind-



RATCHET MECHANISM studied by physicist Richard Feynman shows how random bombardment can bring about nonrandom motion. The gas molecules hitting the propeller cause the gear to turn, but which way does it go? If the spring-loaded pawl—the arm that jams the gear—works correctly, the gear can only turn counterclockwise. But when thermal noise causes the spring to release and reengage, the gear tends to turn clockwise because of the asymmetry of the gear teeth. This effect dominates whenever more heat is applied to the spring than to the gas.

PHILIP HOWE AND KEVIN RING

ing energy. This molecule moved roughly as fast as the normal two-armed kinesin, in support of the Brownian model.

Brownian motion may also play a role in the biomolecular motors that make up our muscles [*see box on page 64*], assemble our proteins, synthesize ATP, zip and unzip DNA, transport proteins across our cell membranes, and break down proteins when they are no longer needed. In some cases, the evidence is equivocal, and researchers still debate what is going on. But one thing is clear: any microscopic machine must either work with Brownian motion or fight against it, and the former seems to be the preferable choice.

The Brownian ratchet principle gives scientists and engineers a whole new way to manipulate matter on a small scale. One of the first applications has been to separate particles by weight. This process

GAMBLER'S PARADOX

THE APPARENT PARADOX of Brownian ratchets—that flip-flopping between two states of a system, each of which independently loses energy, can allow a system to gain energy—also applies to games of chance. Last year physicist Juan M. R. Parrondo of Complutensian University in Madrid and engineer Derek Abbott of the University of Adelaide in Australia came up with a pair of coin games that illustrate the paradox. If you play either game by itself, you tend to lose, but if you randomly switch between them, you tend to win. The trick is that even a losing game lets you win occasionally. By switching games, you lock in those winnings before the inevitable loss takes them away.

Although Parrondo and Abbott's game uses biased coins, other examples require only a standard (unbiased) coin and a fair (not loaded) pair of dice. For instance, consider a game that combines craps with checkers. You play it by moving a piece along part of a checkerboard. The object is to start in the middle and get to the right side before the left side [*below*]. The player moves the piece either forward or backward by rolling a pair of dice and consulting a table of craps-like rules. If the player uses either of the two sets of rules given here—which are identical except for reversing the roles of black and white—he or she tends to lose. The relative probability of winning equals the number of ways to move forward from white to black times the number of ways to move forward from black to white (8×2). Losing involves moving backward twice (5×4). For either set of rules, the player can expect only 80 wins for every 100 losses.

But suppose we allow a coin flip before each move. For heads, the player makes a move according to the first set; for tails, the player uses the second set. Now the probability of winning is the product of the average number of forward moves: $(8 + 2)/2 \times (8 + 2)/2 = 25$. The probability of losing depends on the product of the average number of backward moves: $(4 + 5)/2 \times (4 + 5)/2 = 20.25$. Thus, the player can expect to win 100 times for every 81 times he or she loses.

In this game the dice simulate thermal noise, the unfavorable odds for each game represent the overall driving force, and the coin flip acts as the random input of energy. The game has an asymmetry: according to the first set of rules, the piece tends to spend a longer number on a black square than on a white one, and vice versa for the second set of rules. The coin flip erases this asymmetry. (Sadly, the same trick will not work for two standard casino games, which lack the type of asymmetry that a simple coin toss would eliminate.)

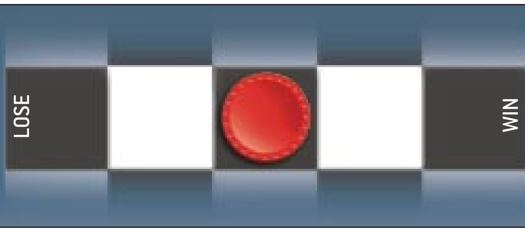
A similar reversal of fortune occurs in many areas of life; statisticians refer to it as Simpson's paradox. It can happen whenever the probabilities of some events are constant while others fluctuate. In the above example, the probability of a backward move is nearly constant while that of a forward move fluctuates depending on the outcome of the coin flip. The paradox has led researchers to draw incorrect conclusions from merged data sets and can lure the naive into subtle investment and insurance scams.

Consider a disaster insurance pool that covers both hurricanes (which tend to strike in late summer and fall) and earthquakes (which can strike year-round). In this simple example, both disasters occur at the same average rate. Floridians and Californians pay a monthly premium, and when disaster strikes, the victims receive a certain fraction of whatever money is in the fund at that time. Wily Floridians might plead that because their businesses are highly seasonal, they should pay less in the fall and winter and, to make up for it, more in the spring and summer. Would that be fair? Surprisingly, no. The Floridians' approach would make the fund larger during hurricane season, so they would tend to get larger payouts than the Californians. Using different rules, clever Californians could tilt the game in their favor. *—R.D.A.*

CRAPS-LIKE GAME involves moving a checkers piece depending on the roll of two dice. The sum on the dice determines the direction of motion. In each of the two rule sets, the piece usually moves backward, but randomly switching between the sets reverses the direction.

RULE SET 1

	WHITE	BLACK
FORWARD	7, 11	11
BACKWARD	2, 3, 12	2, 4, 12



RULE SET 2

	WHITE	BLACK
FORWARD	11	7, 11
BACKWARD	2, 4, 12	2, 3, 12

PHILIP HOWE

Using a QUANTUM RATCHET, researchers could gain precise control of individual electrons.

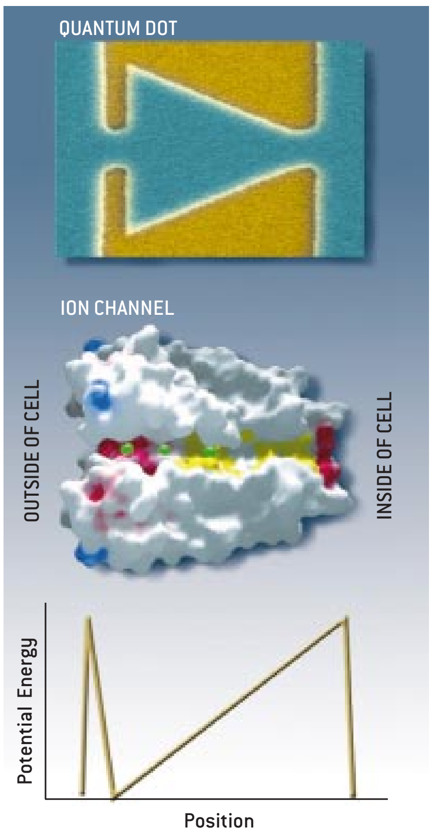
is a microscopic version of panning for gold. When you subject particles to random fluctuations—either by shaking a tray or by subjecting them to Brownian motion—the heavier ones move at a slower speed. The first steps toward building Brownian sieves were taken nine years ago by physicists Armand Ajdari of the Paris School of Industrial Physics and Chemistry and Jacques Prost of the Curie Institute. Recently Joel S. Bader and his colleagues at the biotech company Curagen in New Haven, Conn., built a device to sort DNA molecules. Their approach promises greater precision and selectivity than standard sorting techniques such as electrophoresis, centrifuge and distillation.

In all of the above ratchet examples, the ratchet electric field is either on or off. In 1996, however, Martin Bier and I (both of us then at the University of Chicago) suggested using three states: positive, negative or off. By switching among these states, a Brownian sieve could make heavy particles move one way and light particles the other way. Particles could be continuously fed into the middle of the device, collected at either end, fed into another device tuned to a different mass, and so on, with ever better separation at each stage. Such devices could sort not just by mass but also by size or electric charge. Theorists at Princeton, Chicago, the Massachusetts Institute of Technology and the University of Ottawa have since extended this idea into two dimensions.

Two years ago Alexander van Oudenaarden and Steven G. Boxer, both then at Stanford University, built a working 2-D sieve. They used electron-beam lithography to pattern a glass slide with an array of asymmetric barriers 25 nanometers high. They filled this tiny maze with a fluid of electrically neutral phospholipid molecules, mixed in some phospholipids with various electric charges and applied an electric field. The field pulled the charged molecules through the obstacle course. Because singly charged molecules moved more slowly than doubly charged ones, they had more time to drift sideways while in the space between obstacles. The asymmetric barriers made it easier for them to drift in one direction rather than simply spread out. By the time the charged molecules had reached the other side of the slide, they had sorted themselves into different groups by charge.

A Quantum Leap

IT WAS ONLY a matter of time before ratchets found their way into the quantum world. Four years ago Peter Hänggi and his colleagues at the University of Augsburg in Germany made the tantalizing suggestion that quantum effects—interference between electron wave functions, quantization of energy levels, electron tunneling through barriers—could provide another randomizing force. These effects would take over from Brownian motion at the lowest temperatures and smallest scales. Using a quantum ratchet, researchers could gain precise control of individual electrons without having to exert comparably precise manipulation of electric fields.



TWO RATCHETS differ in detail but may work in basically the same way. The micron-size triangular quantum dot, etched onto a silicon wafer, is a diode—a device that turns alternating current into direct current. The ion channel—a protein molecule shown here as a cutaway surface—is a biological version of a diode, a hundredth the size of the dot. The potential energy profile is thought to be the same for both devices.

Since that time, Charles M. Marcus, then at Stanford, and his colleagues have made an electron pump from a quantum dot, which acts as a tunnel between two larger reservoirs of electrons and can be closed off by electrostatic gates. By cycling the voltage on the dot and on the gates, Marcus's team pushed electrons between the reservoirs one by one. Because their system was always near equilibrium, the process was reversible, allowing the energy usage to be made arbitrarily small.

Two years ago Imre Derényi and I (both of us then at Chicago) designed a similar mechanism in which the voltage changes would be abrupt and random. Such a system would be intrinsically irreversible—the direction an electron is pumped does not depend on the order in which the steps are carried out—and hence more wasteful. But it would have advantages, especially as a model of irreversible chemical reactions, such as those used to drive the ion pump. Other potential applications include electron pumps in molecular computers and amplification of signals along molecule-scale wires.

Meanwhile Heiner Linke, formerly at Lund University in Sweden, and his colleagues have used triangular quantum dots. The triangles acted as ratchets because it was harder for electrons to squeeze through the vertex. When an oscillating voltage modulated this built-in bias, a net current flowed—even though the average voltage was zero. Varying the temperature

HEINER LINKE *University of New South Wales (quantum dot)*; RODERICK MacKINNON *Rockefeller University* IN DECLAN A. DOYLE ET AL., *SCIENCE*, VOL. 280; 1998, © 1998 AAAS *(ion channel)* regulated the direction of the current. At high temperatures the device functioned as a thermal ratchet: the electrons tended to flow out of the vertex of the triangles because once through the vertex it was harder for them to go back. At low temperatures it turned into a quantum ratchet: electrons flowed out of the base of the triangles because the width of the energy barrier was smaller in that direction, thereby making tunneling faster. In addition to their applications in electronics, quantum ratchets could be used to damp the current vortices that develop in superconductors, thus resolving a major problem for magnets and superconducting wires.

These ideas bring us full circle. A century ago Brownian motion helped tremendously in demonstrating the existence of atoms. It also explained chemical reaction rates as a balance between thermal noise, which brings molecules together, and electric repulsion, which pushes them apart. The concepts filtered into biology as a possible explanation of biological transport driven by nonequilibrium chemical reactions. Nowadays biological systems are inspiring the design of chemically synthesized molecular motors and pumps, sophisticated sieves and quantum rectifiers. The flow of ideas has reversed, and the progress is anything but random. In the near future, using the principles of chemistry rather than of mechanical engineering, we may have micron-size factories assembling nanometer-size parts for motors to perform microscopic surgery; pumps to rid the factories (and maybe our cells) of unwanted waste products; and transistors for molecular computers to control these and other processes. Just as in *The War of the Worlds*, which ends with the Martians being felled by humble germs, the small may end up conquering the large. SA

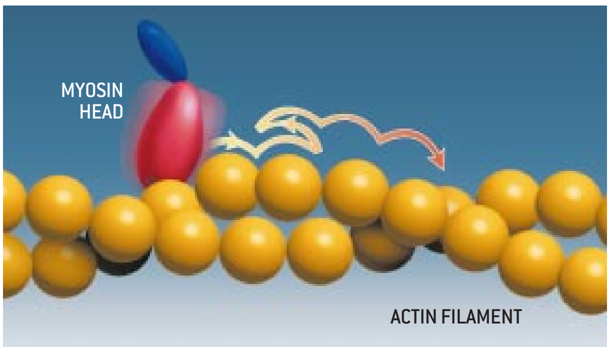
MUSCLING IN by Toshio Yanagida

ONE OF THE UNEXPECTED SUCCESSES of the theory of Brownian ratchets has been a new explanation for muscle contraction. Biomedical researchers have long known that flexing a muscle causes two kinds of filaments, made of proteins called myosin and actin, to slide along each other. The molecules convert chemical energy—in the form of adenosine triphosphate (ATP)—into kinetic energy with an efficiency of about 50 percent. This process works even if the chemical energy is barely more powerful than the noise represented by ambient heat. In contrast, artificial machines such as electric motors and car engines operate at energies much higher than the thermal noise. How can molecular motors be so efficient?

A long-held theory says that muscles contract when a molecule of myosin cleaves a molecule of ATP, gains energy and changes shape. In the process, it pulls an actin filament along by a single step—rather like climbing a ladder. This model is still popular because it posits that muscle contraction is, like the operation of ordinary motors, an easy-to-understand, deterministic process. The problem, however, is that an ordinary motor should get less, not more, efficient as it is shrunk.

To resolve this contradiction, we developed new technologies to manipulate molecules and to identify tiny movements and forces: fluorescent labeling, special short-range lighting called an evanescent field, laser trapping, and scanning probes. These efforts finally bore fruit four years ago.

We discovered that myosin and actin do not, in fact, behave deterministically. The myosin hopped stochastically in steps from 5.5 to 27.5 nanometers long. Each step was a multiple of 5.5 nanometers, equal to the separation of actin molecules in a filament. A step, no matter how long, corresponded to the consumption of a single ATP molecule. Sometimes the myosin even jumped backward rather than forward. These findings are hard to account for with the traditional model but are quite consistent with a Brownian ratchet. Although many questions remain—for example, how exactly does ATP transform the random Brownian motion into forward movement?—the basic picture explains how muscle contractions can be so efficient: rather than trying to overcome noise, they exploit it.



MOTION OF MYOSIN, crucial to the functioning of animal muscle, shows not just forward but also backward and multiple jumps—as expected if random molecular bombardment plays a major role.

PHILIP HOWE

Toshio Yanagida, one of the leading experimentalists in biophysics, is a professor at Osaka University Graduate School of Medicine.

MORE TO EXPLORE

The Laws of the Game. Manfred Eigen and Ruthild Winkler. Princeton University Press, 1993.

The Second Law. P. W. Atkins. W. H. Freeman and Company, 1994.

Thermodynamics and Kinetics of a Brownian Motor. R. Dean Astumian in *Science*, Vol. 276, pages 917–922; May 9, 1997.

A Single Myosin Head Moves along an Actin Filament with Regular Steps of 5.3 Nanometres. K. Kitamura, M. Tokunaga, A. H. Iwane and T. Yanagida in *Nature*, Vol. 397, pages 129–134; January 14, 1999.

Warmth Disperses and Time Passes: A History of Heat. Hans Christian Von Baeyer. Random House, 1999.

Playing Both Sides. Erica Klarreich in *The Sciences*, Vol. 41, No. 1, pages 25–29; January/February 2001.

For a simulation of a basic ratchet, visit **monet.physik.unibas.ch/~elmer/bm**

Slowing a beam of light to a halt may pave the way for new optical communications technology, tabletop black holes and quantum computers

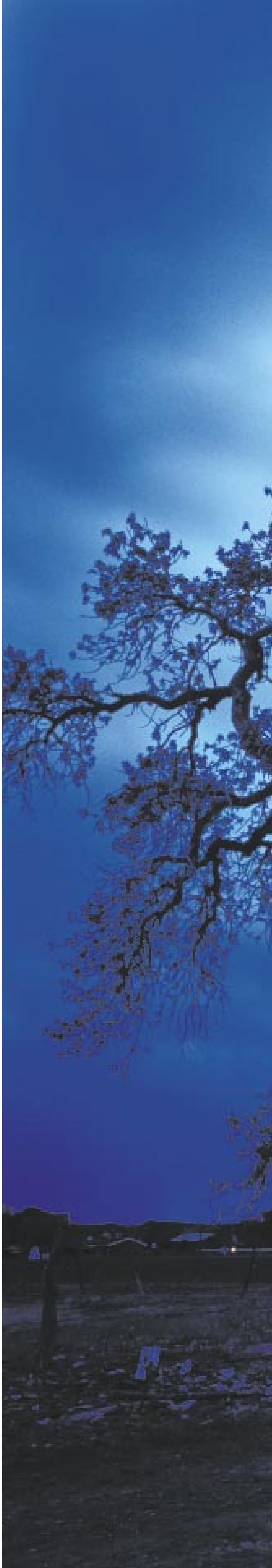
Frozen LIGHT

EVERYONE KNOWS OF THE SPEED OF LIGHT AS one of the unshakable properties of the universe. It's not surprising, then, that experiments to radically alter light's speed require some serious equipment and hard work. Running such an experiment requires first a careful tune-up and optimization of the setup and then a long period of painstaking data gathering to get a consistent set of measurements. At the Rowland Institute for Science in Cambridge, Mass., our original slow-light experiments typically took place in stints lasting 27 hours nonstop. Instead of breaking for meals, we learned to balance a slice of pizza in one hand, leaving the other clean to flip mirrors in and out on the optics table during 38 seconds of total darkness at a crucial stage of each run.

Our goal was to drastically slow down light, which travels through empty space at the universe's ultimate speed limit of nearly 300,000 kilometers a second. We saw the first sign of light pulses slowing down in March 1998. As happens so often in experimental physics—because it can take so many hours to get all the components working together for the first time—this occurred in the wee hours of the morning, at 4 A.M. By July we were down to airplane speed. At that time I had to go to the Niels Bohr Institute in Copenhagen to teach a class. I remember sitting in the plane marveling that I was traveling "faster than light"—that I could beat one of our slow pulses to Denmark by a full hour.

Needless to say, I was restless during the week in Copenhagen and eager to get back to Cambridge to continue the light-slowing experiments. In the next month we reached 60 kilometers per hour and decided that it was time to publish. The real payoff for the hard work, prior to those results, was sitting in the lab in the middle of the night and observing the slow-light pulses, knowing that we were the first in the world to see

BY LENE VESTERGAARD HAU • Photoillustrations by Chip Simons



FREEZING OF LIGHT begins with a process in which a carefully tuned laser beam renders an opaque material transparent to a second laser beam.

light go so slowly that you could outpace it on a bicycle.

Late last year we took this process to its logical but amazing conclusion: we brought pulses of light to a complete halt within tiny gas clouds cooled to near absolute zero. We could briefly keep the pulses on ice, so to speak, and then send them back on their way.

As well as being of great intrinsic interest, slowing and freezing light have a number of applications. At sufficiently low temperatures the ultracold clouds of atoms used in our slow-light experiments form Bose-Einstein condensates, remarkable systems in which all the atoms gather in a single quantum state and act in synchrony. New studies of Bose-Einstein condensates will be made possible by, for example, sending a light pulse through a condensate as slowly as a sound wave, which we expect will cause a wave of atoms to "surf" on the light pulse.

The slow and frozen light work also opens up new possibilities for optical communications and data storage and for quantum-information processing—that is, for quantum computers, which would utilize quantum phenomena to outperform conventional computers. The freezing-light system essentially converts between motionless forms of quantum information and photons flying around at the usual speed of light.

Getting Atoms into a State

MANY ORDINARY MATERIALS slow down light. Water, for instance, slows light to about 75 percent of its velocity in a vacuum. But that type of speed reduction, associated with a material's refractive index, is limited. Diamond, which has one of the highest refractive indices of a transparent material, slows light by a factor of only 2.4. Reducing light's speed by factors of tens of millions requires new effects that depend on quantum mechanics. My group produces the conditions for these effects in a cigar-shaped cloud of sodium atoms—typically 0.2 millimeter long and 0.05 millimeter in diameter—trapped in a magnetic field and cooled to within a millionth of a degree of absolute zero.

Sodium belongs to the family of alkali atoms, which have a single outermost, or valence, electron. The valence electron produces almost all the action: Different excited states of a sodium atom correspond to that electron's being promoted to larger orbits around the nucleus, with higher energies than its usual lowest energy state, or ground state. These states determine how the atom interacts with light—which frequencies it will absorb strongly and so on. In addition, both the valence electron and the atom's nucleus are magnets, in effect acting like tiny compass needles. The electron's magnetism is associated with its intrinsic angular momentum, or spin, a little like the association of the earth's rotational axis with magnetic north but with exact alignment. The precise energies of an atom's excited states depend on how the spins of the nucleus and the valence electron are aligned.

Although an atom can assume a multitude of such states, we use only three of them to slow light. In our experiments, when we finish preparing and cooling the atom cloud, every atom is in state 1, its ground state: the valence electron is in its lowest orbit, and its spin is exactly opposite, or anti-aligned, with the nuclear spin. Also, the total magnetism of each atom is anti-aligned with the magnetic field that we use to hold the cloud in place. State 2 is a very similar state, just with the electron and nuclear spins aligned, which raises the atom's energy a little. State 3 has about 300,000 times more energy than state 2 and is produced by boosting the valence electron up to a larger orbit. Atoms relaxing from state 3 down to state 1 or 2 generate the characteristic yellow glow of sodium streetlights.

The pulse of light that we wish to slow is tuned to the energy difference between states 1 and 3. If we sent a pulse of that light into the cloud without doing any other preparation, the atoms would completely absorb the pulse and jump from state 1 to state 3. After a brief time, the excited atoms would relax by reemitting the light, but at random and in all directions. The cloud would glow bright yellow, but all information about the original pulse would be obliterated.

To prevent this absorption, we use electromagnetically induced transparency, a phenomenon first observed in the early 1990s by Stephen E. Harris's group at Stanford University. In electromagnetically induced transparency, a laser beam with a carefully chosen frequency shines on the cloud and changes it from being as opaque as a wall to being as clear as glass for light of another specific frequency.

The transparency-inducing beam, or coupling beam, is tuned to the energy difference between states 2 and 3. The atoms, in state 1, cannot absorb this beam. As the light of the probe pulse, tuned to state 3, arrives, the two beams shift the atoms to a quantum superposition of states 1 and 2, meaning that each atom is in both states at once. State 1 alone would absorb the probe light, and state 2 would absorb the coupling beam, each by moving atoms to state 3, which would then emit the light at random. Together, however, the two processes cancel out, like evenly matched competitors in a tug of war—an effect called quantum interference. The superposition state is called a dark state because the atoms in essence cannot see the beams (they remain "in the dark"). The atoms appear transparent to the probe beam because they cannot absorb it in the dark state. Which superposition is dark—what ratio of states 1 and 2 is needed—varies according to the ratio of light in the

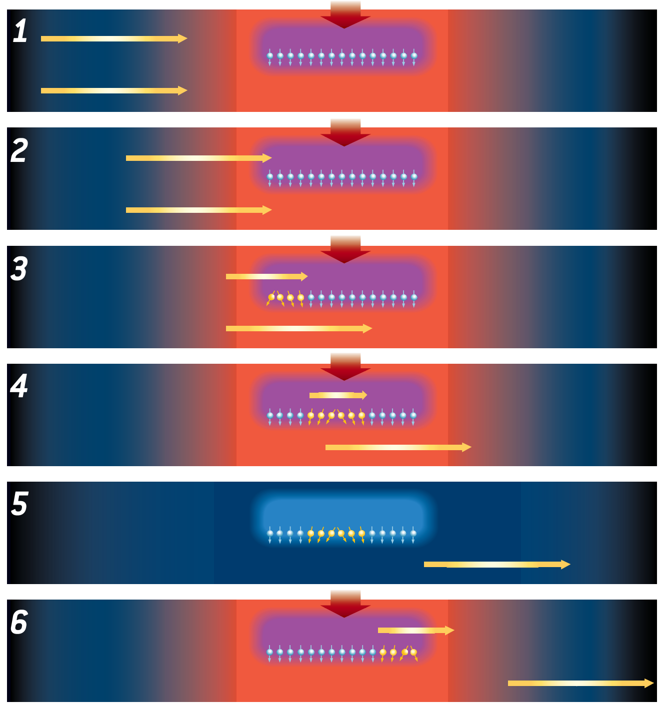
Overview / *Stopping Light*

- Nothing travels faster than light in a vacuum, but even light is slowed down in many media. Scientists have manipulated clouds of atoms with lasers so that pulses of light travel through the clouds at one twenty-millionth of their normal speed—slower than highway traffic.
- A similar technique completely halts the pulses, turning them into a quantum imprint on the atoms. Later, another laser beam converts the frozen pulse back into a moving light pulse with all the properties of the original.
- The process of slowing and stopping light has many research and technological applications.

coupling and probe beams at each location. But once the system starts in a dark state (in this case, 100 percent coupling beam and 100 percent state 1), it adjusts to remain dark even when the probe beam lights up.

A similar cancellation process makes the refractive index exactly one—like empty space—for probe light tuned precisely to state 3. At very slightly different frequencies, however, the cancellation is less exact and the refractive index changes. A short pulse of light "sniffs out" this variation in the index because a pulse actually contains a small range of frequencies. Each of these frequencies sees a different refractive index and therefore travels at a different velocity. This velocity, that of a continuous beam of one pure frequency, is the phase velocity. The pulse of light is located where all these components are precisely in sync (or, more technically, in phase). In an ordinary medium such as air or water, all the components move at practically the same velocity, and the place where they are in sync—the location of the pulse—also travels at that speed. When the components move with the range of velocities that occurs in the transparent atoms, the place where they are in sync gets shifted progressively farther back; in other words, the pulse is slowed. The velocity of the pulse is called the group velocity, because the pulse consists of a group of beams of different frequencies.

This process differs in a number of important respects from the usual slowing of light by a medium with a refractive index greater than one: the group velocity is slowed, not the phase velocity; the very steep variation of the refractive index, not a large value of the index itself, causes the slowing; and the coupling laser beam has to be on the entire time.



WAYLAYING LIGHT: Before the light pulse (*yellow*) reaches the cloud of atoms (*blue*) that will freeze it, all the atoms' spins (*small arrows*) are aligned and a coupling laser beam (*red*) renders the cloud transparent to the pulse (*1, 2*). The cloud greatly slows and compresses the pulse (*3*), and the atoms' states change in a wave that accompanies the slow light. When the pulse is fully inside the cloud (*4*), the coupling beam is turned off (*5*), halting the wave and the light; at zero velocity the light vanishes. Later (*6*) the coupling beam is turned on again, regenerating the light pulse and setting the wave and the light back in motion.

SAMUEL VELASCO

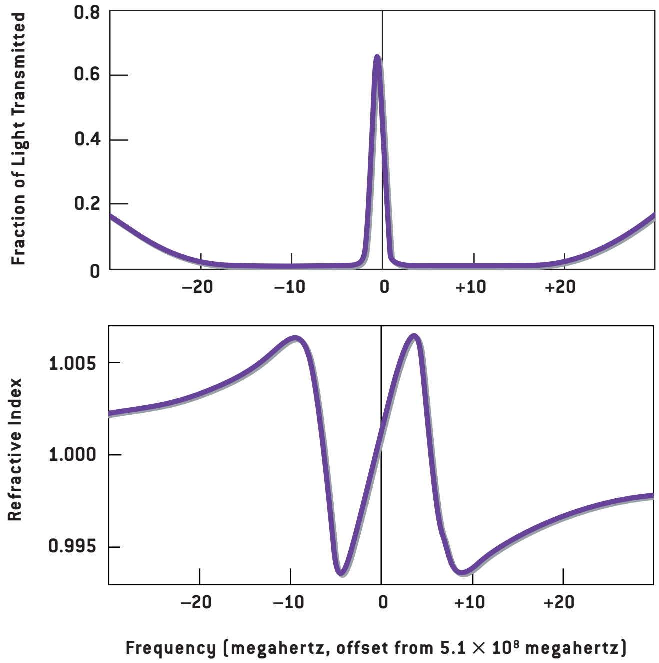
Ultracold Atoms for Freezing Light

THE MORE RAPIDLY the refractive index changes with frequency, the slower the pulse travels. How rapidly the index can change is limited by the Doppler effect: the incessant motion of the atoms in the gas smears out each state across a small range of energies. The Doppler effect is like the change in tone of a siren moving toward or away from you. Imagine the cacophony of tones you would hear if many police cars were racing toward and away from you at various speeds.

My research group uses extremely cold atoms (which move slowly) to minimize this Doppler spreading. Consequently, the energy states are sharply defined, and the frequency range where cancellation occurs can be made narrow. Slow light in room-temperature gases has been obtained by Marlan O. Scully's group at Texas A&M University, Dmitry Budker's group at the University of California at Berkeley, and the group at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Mass., led by Ronald L. Walsworth and Mikhail D. Lukin. The use of hot atoms saves these groups from having to produce ultracold atoms, but it limits their ability to slow light.

We chill our sodium atoms with a combination of laser beams, magnetic fields and radio waves. The atoms first emerge from a hot source as an intense beam, traveling about 2,600 kilometers an hour. A laser beam hits the atoms head-on and in a millisecond slows them to 160 kilometers an hour—a deceleration of 70,000 gravities produced by a laser beam that wouldn't burn your finger. Further laser cooling in an optical molasses—six beams bathing the atoms from all sides—chills the atoms to 50 millionths of a degree above absolute zero. In a few seconds we accumulate 10 billion atoms in the molasses. Next we turn off the laser beams, plunging the lab into total darkness, and turn on electromagnets, whose combined field holds the atom cloud like a trap. For 38 seconds we cool the atoms through evaporation, kicking out the hotter atoms and leaving the cooler ones behind. Specially tuned radio waves help to speed the hot atoms on their way. This whole process—from hot beam to cold, trapped atoms—takes place inside a vacuum chamber pumped out to 10^{-14} (10 quadrillionths) of atmospheric pressure.

When we cool the cloud to about 500 billionths of a degree, it forms a Bose-Einstein condensate, a very odd state of matter in which the several million atoms left after the evaporative cooling behave in a completely synchronized fashion [see "The Coolest Gas in the Universe," by Graham P. Collins; SCIENTIFIC AMERICAN, December 2000]. These ultracold atom clouds, freely suspended in the middle of the vacuum chamber by a magnetic field, are the coldest places in the universe. And



OPTICAL PROPERTIES induced in a cloud of atoms by a carefully tuned laser beam are the key to the light-slowing process. A coupling laser beam passing through the cloud makes it transparent to light of a precise frequency (*top*) and causes an associated sharp variation of its refractive index (*bottom*). The transparency allows properly tuned light to pass through the cloud without being absorbed, and the steeper the change in the refractive index, the slower the light travels.

yet the rest of our experimental setup, within one centimeter of the cloud, is at room temperature. Vacuum-sealed windows on the chamber let us see the atoms directly by eye during laser cooling: a cold atom cloud in optical molasses looks like a little bright sun, five millimeters in diameter. Such easy optical access allows us to massage the atoms with laser beams and make them do exactly what we want.

When our cigar of cold atoms is in place, we illuminate it from the side with the coupling laser. Then we launch a probe pulse along the axis of the cigar. To measure the speed of the light, we do the most direct measurement imaginable: we sit behind the atom cloud with a light detector and wait for the light pulse to come out, to see how long it takes. Immediately after the pulse has gone through, we measure the length of the cloud with yet another laser beam, shone from below to project the cloud's shadow onto a camera. That length divided by the delay of the pulse gives us the velocity. The delays are typically in the range of microseconds to milliseconds; this might sound short, but it is equivalent to light taking a detour through kilometers of optical fiber wound in a coil.

When we slow a light pulse down by a factor of 20 million, more happens than just a change of speed. At the start our pulse of light is a kilometer long, racing through the air at nearly 300,000 kilometers a second. (Of course, our laboratory's length is much less than a kilometer, but if we could place our laser that far away, its pulses would be that long in the air.) The pulse's leading edge crosses the glass window into the vacuum chamber and enters our levitating speck of sodium atoms. Inside this tenuous cloud the light travels at 60 kilometers an hour. A cyclist on a racing bike could overtake such sluggish light.

Through the Gas, Darkly

WITH THE FRONT of the light pulse traveling so slowly and its tail still going full tilt through the air, the pulse piles into the gas like a concertina. Its length is compressed by a factor of 20 million to a mere twentieth of a millimeter. You might expect the light's intensity to increase greatly because the same amount of energy is crammed into a smaller space. This amplification does not happen, however; instead the electromagnetic wave remains at the same intensity. Put another way, in free space the pulse contains 50,000 photons, but the slow pulse contains 1/400 of a photon (the factor of 20 million again). What has happened to all the other photons and their energy? Some of that energy goes into the sodium atoms, but most of it is transferred to the coupling laser beam. We have monitored the coupling laser's intensity to observe this energy transfer directly.

These transfers of energy also change the states of the sodium atoms where the pulse is passing by. At the front of the pulse the atoms are changed from their original state 1 to a superposition of states 1 and 2, the dark state discussed above. The dark state has the largest proportion of state 2 at the central, most intense part of the pulse. As the rear of the slow pulse leaves a region of atoms, the atoms change back to state 1. The pattern of dark states in the cloud mimics the form of the compressed slow-light pulse and accompanies it through the gas as a wave. When this wave and the light pulse reach the end of the gas cloud, the light pulse sucks energy back out of the atoms and the coupling beam to dash away through the air at its customary 300,000 kilometers a second, restored to its original kilometer of length.

The velocity of the slow light depends on several parameters. Some of the parameters are fixed once we choose our atom species and which excited states to use, but two of the variables are under our control: the density of the atom cloud and the intensity of the coupling laser beam. Increasing the cloud's density decreases the light's speed, but we can push that only so far, in part because very dense clouds leak atoms out of the magnetic trap too rapidly. The pulse speed is also reduced if the coupling laser beam is weaker. Of course, if the coupling laser is

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GRAPHS BY LAURIE GRACE

BLACK HOLE: Slow light drawn into a whirlpool of atoms could simulate phenomena expected in the warped spacetime near black holes.

WHENEVER WE MENTION THE SPEED OF LIGHT in these pages, readers send us questions. Here we try to lay a few perennial puzzles to rest. More are tackled online at www.sciam.com/2001/0701issue/0701haubox1.html

I read that charged particles traveling faster than light emit Cerenkov radiation—but how can anything go faster than light? Isn't it supposed to be the universal speed limit?

This goes to the heart of much confusion about the speed of light. "The speed of light" has two quite distinct meanings. One is "the speed at which light travels," and that speed varies depending on the medium: fastest in a vacuum, a tiny bit slower in air, two thirds as fast in glass.

The second meaning, the universe's speed limit, is phrased more carefully as "the speed of light in a vacuum" and is given its own symbol: *c*. The velocity *c* seems to be an absolute, unchanging quantity. The speed at which light travels through a vacuum is only one of *c*'s manifestations, however. We call *c* the speed of light only because of the historical accident that scientists first encountered *c* in its role as the velocity of light and other electromagnetic waves. Some physicists advocate renaming *c* "Einstein's constant."

When we distinguish these two speeds of light, the conditions for Cerenkov radiation are no puzzle. In water, light travels at about 0.75 *c*. Particles can go faster than that through water without breaking the speed limit of 1.00 *c*.

What is the speed of light?

c is *exactly* 299,792,458 meters per second.

Exactly? How can it be a whole number?

Some metrological sleight of hand is at work: nowadays the meter is defined as the distance light travels in a vacuum in 1/299,792,458 of a second. Metrologists define the meter that way because doing so results in a quantity that is more precise than the alternatives.

Why is *c* a speed limit anyway?

This relates to the real importance of *c*: it defines a fundamental relation between space and time. A distance of 299,792,458 meters is equivalent to a time interval of one second. This is one of the messages of Einstein's theory of special relativity: space and time are different aspects of a single entity called spacetime.

In spacetime, if one can travel faster than *c*, one can devise ways to travel through time into the past. Time travel would unleash logical paradoxes of cause and effect, which convinces many physicists that such travel (and even transmission of information faster than *c*) must be impossible. There are other reasons or clues as well (see our Web site), not least of which is the lack of evidence of any physical object or signal traveling faster than *c*. —*Graham P. Collins, staff writer and editor*

too feeble, the cloud will not be transparent and it will absorb the pulse. Nevertheless, we have a trick that lets us achieve the ultimate in slowing without losing the pulse to absorption: turning off the coupling laser beam while the compressed slowed pulse is in the middle of the gas.

In response, the light pulse comes to a grinding halt and turns off. But the information that was in the light is not lost. That information was already imprinted on the atoms' states, and when the pulse halts, that imprint is simply frozen in place, somewhat like a sound recorded on a magnetic tape. The stopping process does not compress the pattern of states, because all of it slows down in unison, unlike the earlier stage wherein the pulse gradually entered the gas.

The frozen pattern imprinted on the atoms contains all the information about the original light pulse. For example, the ratio of states 1 and 2 relates to the intensity of the pulse at each location. We effectively have a hologram of the pulse written in the atoms of the gas. This hologram is read out by turning the coupling laser on again. Like magic, the light pulse reappears and sets off in slow motion again, along with the wave of atoms' states, as if nothing had interrupted it.

We can store the light for up to a millisecond, long enough for a pulse to travel 300 kilometers in air. The pulse does become degraded the longer it is stored: the atoms in the gas are still moving around, causing the pattern of dark states to diffuse slowly. In addition, collisions between atoms can disrupt the superposition states. After a millisecond, the resulting output pulse is distinctly weaker than the original. We can also play some tricks. For instance, if the coupling beam is turned on to a higher intensity, the output pulse will be brighter but shorter. Turning the coupling beam on and off quickly several times regenerates the pulse in several pieces. Such manipulations demonstrate the degree of control that we have over our stored pulses and may be useful in future experiments and applications.

Black Holes and Computers

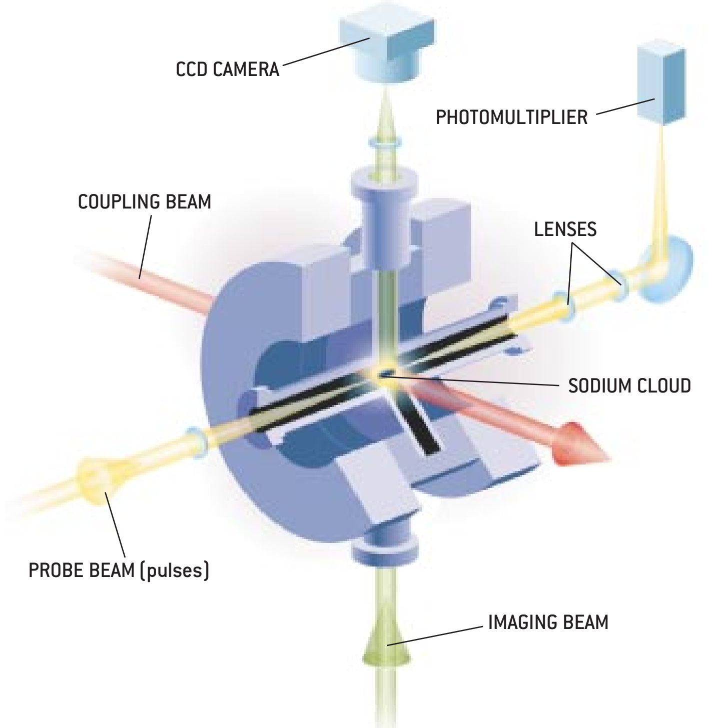
THE PROCESS OF SLOWING and stopping light opens up many interesting experiments. For example, we could send a light pulse through a Bose-Einstein condensate with the light speed adjusted to match the speed of sound in the condensate (around one centimeter a second). Atoms of the condensate should surf along with the light pulse, setting off oscillations of the entire condensate. This would be a completely new way to study superfluid properties of condensates. Condensates can also be produced in a vortex state, wherein the gas rotates, reminiscent of water going down the drain. A pulse of slow light traveling through a vortex would find itself dragged along with the gas—very similar to a phenomenon expected to occur near black holes. With slow light, we can study this and some other black hole phenomena in the laboratory.

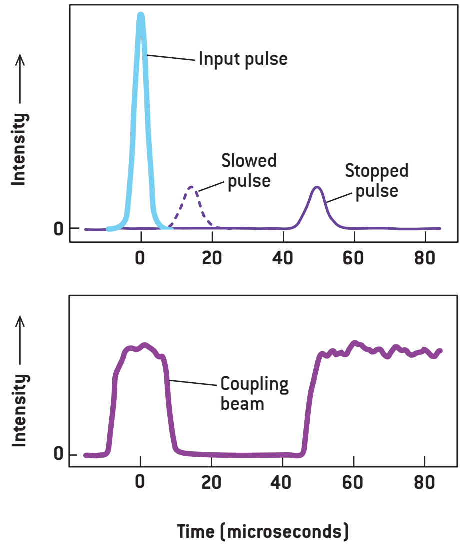
Slow light also enables a new kind of nonlinear optics, which occurs, in particular, when one laser beam alters the properties of another beam. Nonlinear optics is a huge field of research, both of fundamental interest and with applications from imaging to telecommunications. Extremely intense beams

A BENCHTOP GUIDE TO STOPPING LIGHT

EXPERIMENTAL SETUP

Three laser beams and an ultracold cloud of sodium atoms (*size exaggerated*) in a high vacuum lie at the heart of the slow-light experiment. The coupling beam interacts with the cloud, making it transparent but molasseslike to a pulse of the probe beam. A photomultiplier tube measures the pulse's time of arrival to better-than-microsecond precision. The imaging beam then measures the length of the cloud by projecting its shadow onto a camera. Not shown are the system that delivers and cools a new ultracold cloud for each pulse, electromagnets whose combined field holds the atoms in place, and additional details of the optics.





WHAT STOPPED LIGHT LOOKS LIKE

The precise times of detection of light pulses reveal the slowing and stopping of light. With no atom cloud present, the input pulse is detected at time "zero" (*top*). Slowing of the pulse by a cloud is revealed by the pulse's delay (*dotted curve*). To stop a pulse, the coupling beam (*bottom*) is turned off while the pulse is inside the cloud. The time that the pulse is stopped—in this case, about 35 microseconds—adds to its delay. Slowed pulses lose intensity because the cloud is not perfectly transparent. Also, stopped pulses gradually degrade because of diffusion and collisions of the atoms holding them.

are usually needed to achieve nonlinear optical effects, but with slow light the corresponding phenomena can be produced with a very small number of photons. Such effects could be useful for creating ultrasensitive optical switches.

Another application for slow and stopped light could be quantum computers, in which the usual definite 1's and 0's are replaced with quantum superpositions of 1's and 0's called qubits. Such computers, if they can be built, would be able to solve certain problems that would take an ordinary computer an enormously long time. Two broad categories of qubits exist: those that stay in one place and interact with one another readily (such as quantum states of atoms) and those that travel rapidly from place to place (photons) but are difficult to make interact in the ways needed in a quantum computer. The slow-light system, by transforming flying photons into stationary dark state patterns and back, provides a robust way to convert between these types of qubits, a process that could be essential for building large-scale quantum computers. We can imagine imprinting two pulses in the same atom cloud, allowing the atoms to interact, and then reading out the result by generating new output light pulses.

Even if frozen light doesn't prove to be the most convenient and versatile component for building a quantum computer, it has opened up more than enough research applications to keep us—and other groups—busy for many more all-night sessions in the years to come. SA

MORE TO EXPLORE

Electromagnetically Induced Transparency. Stephen E. Harris in *Physics Today,* Vol. 50, No. 7, pages 36–42; July 1997.

The Bose-Einstein Condensate. Eric A. Cornell and Carl E. Wieman in *Scientific American,* Vol. 281, No. 3, pages 40–45; March 1998.

Light Speed Reduction to 17 Metres per Second in an Ultracold Atomic Gas. Lene Vestergaard Hau, S. E. Harris, Zachary Dutton and Cyrus H. Behroozi in *Nature,* Vol. 397, pages 594–598; February 18, 1999.

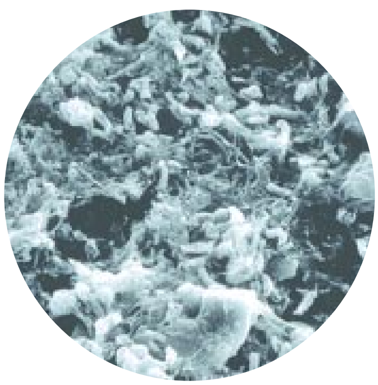
Observation of Coherent Optical Information Storage in an Atomic Medium Using Halted Light Pulses. Chien Liu, Zachary Dutton, Cyrus H. Behroozi and Lene Vestergaard Hau in *Nature,* Vol. 409, pages 490–493; January 25, 2001.

GRAPHS BY LAURIE GRACE; EXPERIMENTAL SETUP BY SAMUEL VELASCO

BY J. W. COSTERTON AND PHILIP S. STEWART
Photographs by Sam Ogden

Battling Biofilms

THE WAR IS AGAINST BACTERIAL COLONIES THAT CAUSE SOME OF THE MOST TENACIOUS INFECTIONS KNOWN. THE WEAPON IS KNOWLEDGE OF THE ENEMY'S COMMUNICATION SYSTEM



CONTACT LENSES (*left*) are among the familiar surfaces that may be colonized by biofilms—slime-enclosed communities of microorganisms. The film shown above, from a contact lens case, presumably caused a corneal infection diagnosed in the lens wearer.

MICROGRAPH: LOUISE McLAUGHLIN-BORLACE *Institute of Ophthalmology, Department of Pathology, London;* LICENSED FOR USE, ASM MicrobeLibrary (www.microbelibrary.org)

Pentagon planners concern themselves a great deal nowadays with information warfare. Why? Because interfering with a foe's ability to communicate can be far more effective than destroying its bunkers or factories. In the battle against harmful bacteria, some investigators are considering the same strategy.

The microbes that cause many stubborn infections organize themselves into complex and tenacious films—biofilms—that can be nearly impossible to eradicate with conventional antibiotics. In the past few years, medical researchers have discovered that the microorganisms in biofilms depend critically on their ability to signal one another. Drugs able to interfere with this transmission might then bar the microbes from establishing infections or undermine their well-fortified positions; such drugs might thus combat maladies ranging from the pneumonia that repeatedly afflicts people with cystic fibrosis to the slow-burning infections that often form around medical implants.

Signal-dampening compounds are currently being evaluated in animal studies, but why is it that such elegant weapons are only now being readied to enter the medical arsenal? The answer, in short, is that microbiologists took a very long time to size up the enemy. Ever since the late 19th century, when Robert Koch's laboratory studies in Germany validated the germ theory of disease, most people, scientists included, have envisioned bacteria as single cells that float or swim through some kind of watery habitat, perhaps part of the human body. This picture emerged from the way investigators usually examine such organisms: by training their microscopes on cultured cells suspended in a fluid droplet. That procedure is convenient but not entirely appropriate, because these experimental conditions do not reflect actual microbial environments. As a result, the bacteria in typical laboratory cultures act nothing like the ones encountered in nature.

In recent years, we and other bacteriologists have gained important insights into how common disease-causing microbes actually live. Our work shows that many of these organisms do not, in fact, spend much time wafting about as isolated cells. Rather they adhere to various wetted surfaces in organized colonies that form amazingly diverse communities.

In retrospect, it is astonishing that investigators could overlook this microbial lifestyle for so long. After all, bacterial biofilms are ubiquitous—dental plaque (which most of us confront daily), the slippery coating on a rock in a stream, and the slime that inevitably materializes inside a flower vase after two or three days are but a few common examples. And bacteria, the focus of our studies, are not alone in the ability to create biofilms. Indeed, the genetic diversity of the microorganisms that can arrange themselves into living veneers and the breadth of environments they invade convince us that this ability must truly be an ancient strategy for microbial growth. Scientific appreciation and understanding of that strategy is, however, a modern phenomenon.

TROUBLE IN TUBES
Biofilms that form in urinary catheters are a common source of infection. When the tubes stay in only briefly, they pose little risk, but the danger increases with prolonged use. A 1996 study found, for example, that after a week, infections strike 10 to 50 percent of catheterized patients; after a month, virtually all such patients are affected.

Germs in Flatland

SOME BIOLOGISTS had, in fact, attempted long ago to examine the bacteria living in biofilms using ordinary microscopes; a handful even employed electron microscopes. They always saw some bacteria, but being unable to obtain clear images from deep within living layers, they concluded that the cells inside were mostly dead and jumbled in random clumps. This view changed little until about a decade ago, when bacteriologists began employing a technique called laser scanning confocal microscopy. That technology enables investigators to view slices at different depths within a living biofilm and to stack these planes together to create a three-dimensional representation.

Applying this approach in a concerted effort to study the structure of biofilms, John R. Lawrence of the Canadian National Water Research Institute, Douglas E. Caldwell of the University of

TROJAN HORSES Despite elaborate precautions, biofilm bacteria sometimes get into biomedical products. In 1993 and 1994, 100 asthmatics died because the albuterol inhalants they were using contained the biofilm-forming bacterium *Pseudomonas aeruginosa.* The source was traced to a tank involved in the manufacture of this drug. In 1989 another well-known biofilm bacterium, *P. cepacia,* colonized bottles of a potent antiseptic (povidone-iodine solution), causing infections in patients at a children's hospital in Texas.

Saskatchewan and one of us (Costerton) demonstrated for the first time in 1991 that the bacteria grow in tiny enclaves, which we called microcolonies. Bacteria themselves generally constitute less than a third of what is there. The rest is a gooey substance the cells secrete, which invariably absorbs water and traps small particles.

The goo—or, more formally, the extracellular matrix—holds each microcolony together. A biofilm is built of countless such groupings, separated by a network of open water channels. The fluid coursing through these tiny conduits bathes each congregation of microbes, providing dissolved nutrients and removing waste products. The cells situated on the outside of a microcolony are well served by this plumbing system, but those in the interior are largely cut off. The dense aggregation of cells surrounding them and the organic matrix that cements things together act as barriers to water flow. So the cells inside the colony must make do with the nutrients than can diffuse inward to them. Actually, the supply is not all that meager: because the glue is mostly just water, small molecules can move through it freely—albeit with certain important exceptions. A substance will have a hard time diffusing to the center of a microcolony if it reacts with the cells or matrix material it encounters along the way.

Such chemical reactivity gives rise to small-scale environmental changes within a biofilm. These variations were recognized even before confocal microscopy revealed the cause. In 1985 our colleague Zbigniew Lewandowski began making direct measurements of chemical conditions in biofilms using needle-shaped microelectrodes with tips just one hundredth of a millimeter across. He found, among other things, that the oxygen concentration varies radically between locations as close as five hundredths of a millimeter apart—little more than the width of a human hair. Scientists often look at the amount of oxygen in a bacterial community because it can reflect the physiological status of the cells. For example, in a biofilm composed solely of *Pseudomonas aeruginosa* (the bacterium responsible for cystic fibrosis pneumonia), cellular activity and growth take place only where oxygen can penetrate—the outer two or three hundredths of a millimeter of each tiny colony. Deeper down, the cells are alive but dormant. This mix of metabolic states differs markedly from the uniformity typically found in laboratory cultures.

The variety of chemical environments that arise within a single biofilm means that one cell may look and act very different from the next even

THE AUTHORS

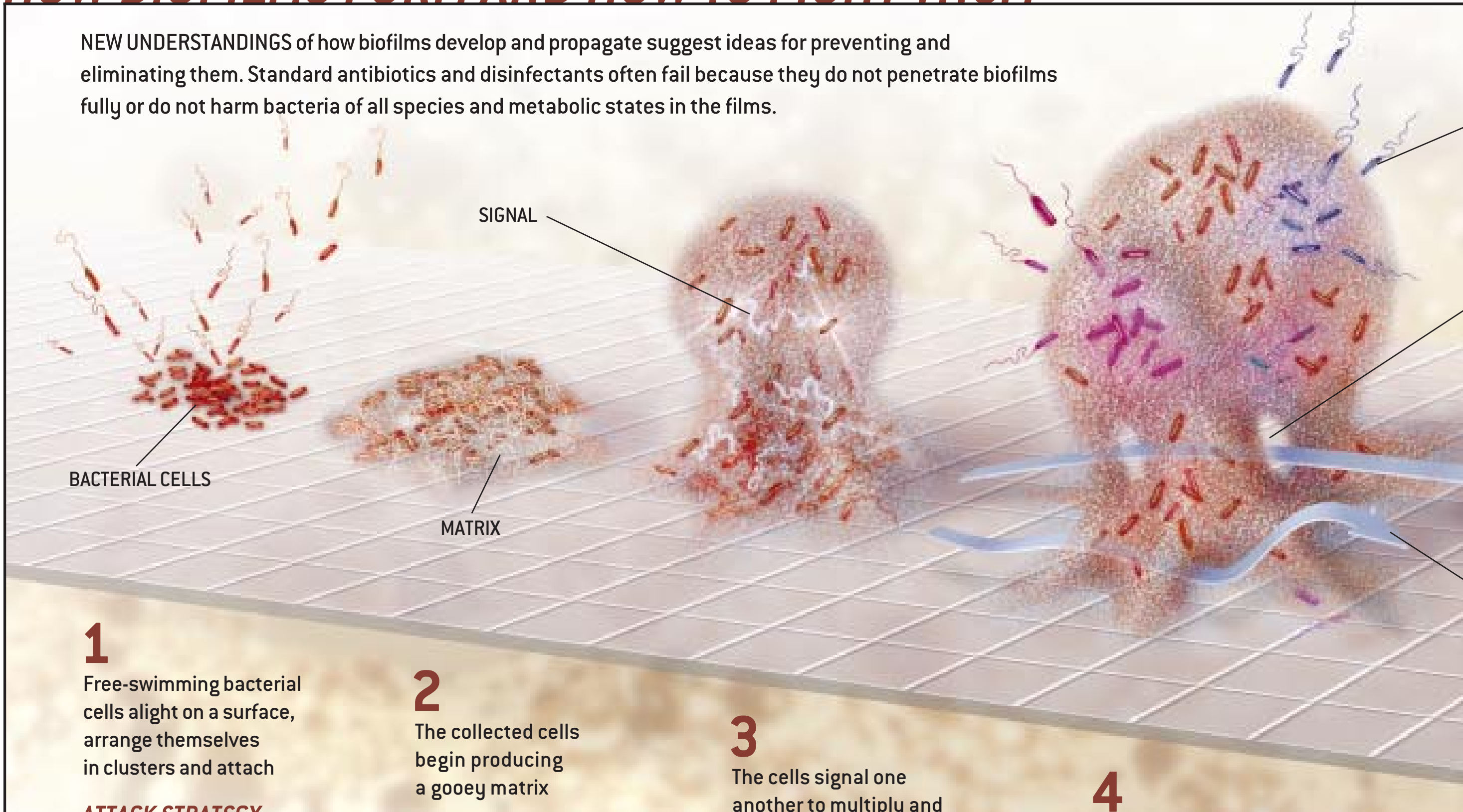
J. W. ("BILL") COSTERTON and *PHILIP S. STEWART* have worked together for almost 10 years. Costerton, who holds a Ph.D. in bacteriology, is head of the Center for Biofilm Engineering at Montana State University. Stewart, whose doctorate is in chemical engineering, is deputy director and research coordinator at the center.

DENTAL PLAQUE is a biofilm. Mounting evidence implicates it, surprisingly, in heart disease.

MICROGRAPH: R. BOS, H. J. BUSSCHER, W. L. JONGEBLOED AND H. C. VAN DER MEI *Laboratory for Materia Technica, University of Groningen, The Netherlands;* LICENSED FOR USE, ASM MICROBELIBRARY (www.microbelibrary.org)

HOW BIOFILMS FORM AND HOW TO FIGHT THEM

NEW UNDERSTANDINGS of how biofilms develop and propagate suggest ideas for preventing and eliminating them. Standard antibiotics and disinfectants often fail because they do not penetrate biofilms fully or do not harm bacteria of all species and metabolic states in the films.



1
Free-swimming bacterial cells alight on a surface, arrange themselves in clusters and attach

ATTACK STRATEGY
Coat surfaces with molecules that block or disrupt microbial arrangement or attachment

2
The collected cells begin producing a gooey matrix

ATTACK STRATEGY
Coat surfaces with substances that interfere with matrix production

3
The cells signal one another to multiply and form a microcolony

ATTACK STRATEGY
Deliver signal blockers to threatened areas to abort biofilm formation

4
Chemical gradients arise and promote the coexistence of diverse species and metabolic states

ATTACK STRATEGY
Deliver multiple antibiotics or disinfectants to undermine the varied survival strategies of biofilm cells

ILLUSTRATION BY KEITH KASNOT

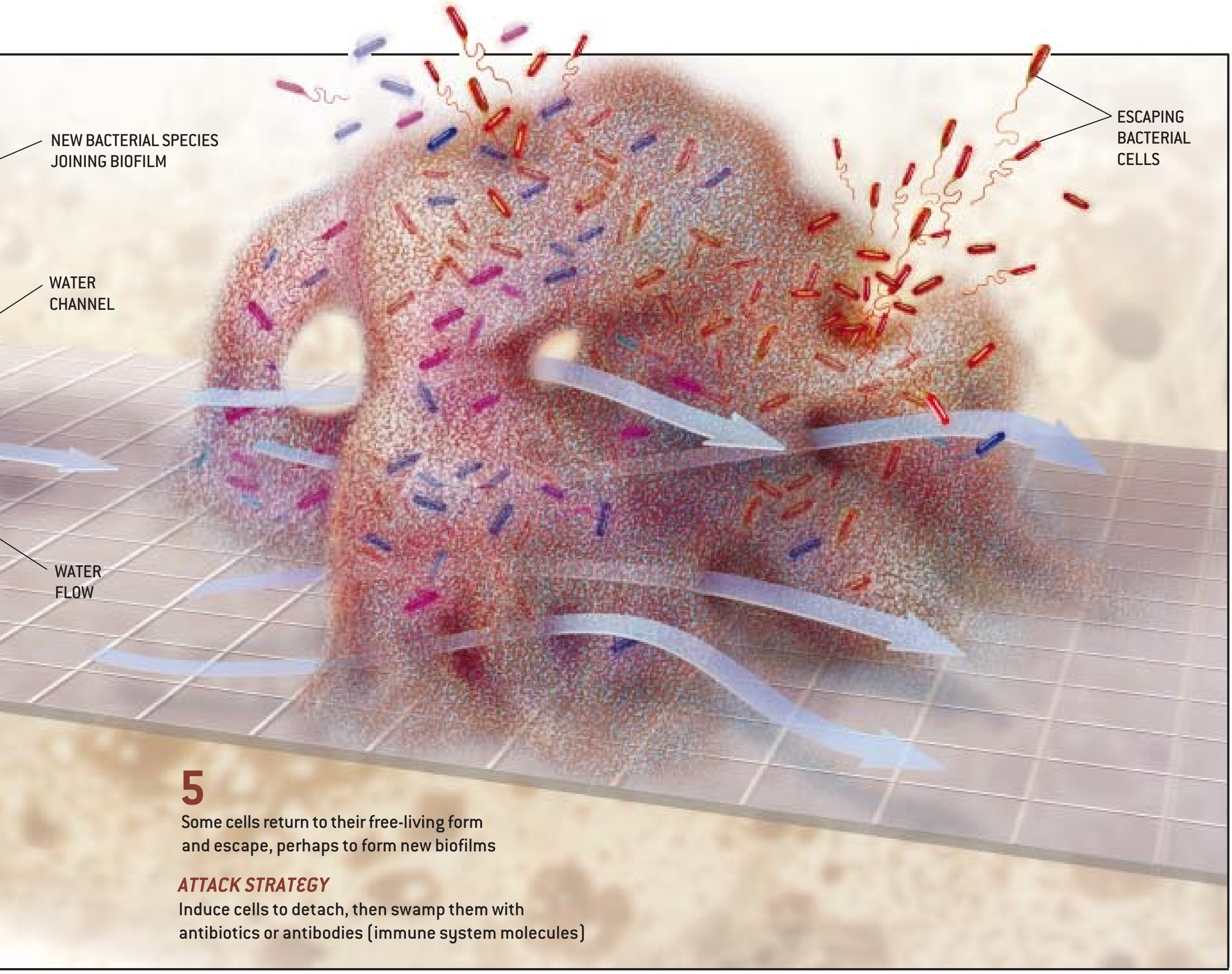
when the two are genetically identical. Similarly, local conditions control the production of many toxins and other disease-causing substances by microbial cells in a biofilm; consequently, some cells may inflict little harm on a host, whereas others may be lethal. The wide range of conditions can also permit several bacterial species to live side by side and thrive. Sometimes one species feeds on the metabolic wastes of another, aiding them both.

An interesting case in point has been understood in a general way since the 1940s: the biofilms that form on fodder after cows or other ruminants eat it. These films are initially made up of organisms that digest the cellulose in plant matter and produce organic compounds called fatty acids. When these cellulose-eating bacteria have generated enough fatty acids to inhibit their own growth, mobile cells of *Treponema* and other species invade the biofilm and begin using these very substances to fuel their own metabolism. The forage material gradually disappears, being converted into a mass of bacteria that the animal digests later on. That is, cows subsist on bacterial biofilms, not hay.

For ruminant animals, these films are clearly indispensable. But for the rest of us, they are a nuisance or, sometimes, a serious threat to health. They can survive most chemical treatments used to control bacteria in medicine and industry, treatments that would quickly eradicate free-floating cells. They can also evade the molecules and cells that the immune system unleashes. Biofilm infections thus tend to be quite persistent.

Tough Bugs

WHY, EXACTLY, are these biofilms so resilient? At times, antibiotics and germ-fighting cleansers may fail to pierce the film. Penicillin antibiotics, for instance, have great difficulty penetrating biofilms containing cells that produce enzymes known as beta-lactamases. These enzymes degrade the an-

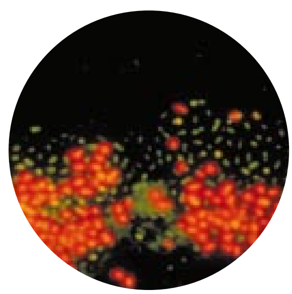


tibiotic faster than it can diffuse inward, so that it never reaches the deeper layers of a biofilm. Even chlorine bleach, a favorite of home and industry, has a hard time eradicating biofilms. This reactive oxidant will eventually burn its way in, but first it must deplete, layer by layer, the neutralizing capacity of the film. That process takes more time and bleach than one might expect. It is easy, therefore, to be lulled into thinking that all bacteria must be dead when many are still alive.

Other factors enhance tenacity as well. Even where an antimicrobial agent penetrates biofilms easily, the microorganisms often still survive aggressive treatment that would eradicate free-floating cells. This ability had long mystified biologists, but lately they have learned that the variety of conditions and bacterial types in a biofilm confers protection against antibacterial agents.

Consider again the action of penicillin, which attacks replicating bacterial cells of many species. If a biofilm contains regions that are, say, starved of an essential nutrient, the cells in those areas, which are alive but not replicating, will survive exposure to penicillin. Because active and inactive microbes are closely juxtaposed in a biofilm, and because surviving bacteria can use dead ones as nutrients, the few cells remaining after the antibiotic therapy ends can restore the biofilm to its original state in a matter of hours.

Such abilities explain why antimicrobials that work fine on cultured cells often do not yield results that are useful to people doing battle with biofilms. Most of these people are physicians and patients, but a large number are engineers who have to contend with the ruinous effects of biofilms in industry, where bacteria often foul machinery and speed the corrosion of metal pipes. To aid both groups, in 1990 the National Science Foundation established the Engineering Research Center (now called the Center for Biofilm Engi-



AFTER 60 MINUTES of exposure to bleach, many cells in this biofilm were dying (*green*), but many others, especially in the interior, still remained active (*red*).

MICROGRAPH: GORDON McFETERS *Center for Biofilm Engineering, Department of Microbiology, Montana State University;* LICENSED FOR USE, ASM MICROBELIBRARY (www.microbelibrary.org) neering) at Montana State University, where the two of us have collaborated for nearly a decade.

Research here has revealed, among other things, that as bacteria adhere to a surface and form a biofilm, they manufacture hundreds of proteins not found in free-floating cells. Some of these proteins are involved in a curious shuffle that the cells carry out just after they settle on a surface but before they fix their positions, as Roberto Kolter and his colleagues at Harvard Medical School have shown by deleting certain genes (the blueprints for proteins) from various bacteria. Using *Staphylococcus epidermidis,* which is responsible for common staph infections, other researchers have identified genes that govern the next step in the development of a biofilm: the synthesis of the extracellular matrix. With these genes inactivated, the bacterium loses its ability to form a biofilm in the test tube and, apparently, in the tissues of laboratory animals.

Recent experiments have revealed similar genetic control centers in other species as well. For example, *P. aeruginosa* contains several genes that are, in essence, turned on within 15 minutes of this bacterium's attachment to a surface. One of these genes, *algC,* is needed to synthesize alginate, the gelatinous polymer that makes up much of the extracellular matrix.

How is it that the cells coming together to form a biofilm know to turn on certain genes in the first place? The answer is that these seemingly simple, autonomous microbes regularly communicate with one another. In *P. aeruginosa* and a broad class of similar bacteria, the relevant signaling molecules are acylated homoserine lactones, which each cell produces at a low level. When enough cells assemble, the concentration of these compounds increases, which in turn triggers changes in the activity of dozens of genes. David G. Davies of Binghamton University has shown that this mechanism, called quorum sensing, is critical for the development of biofilms. Indeed, laboratory strains of *P. aeruginosa* that lack the gene for a particular acylated homoserine lactone fail to build normal biofilms and instead pile up in a disorganized heap.

Investigators have now identified signaling molecules used by biofilms that grow, among other places, on urinary catheters. These films and the films that thrive on permanent medical implants cause the most worrisome types of biofilm infections, affecting perhaps 10 million people in the U.S. every year. Despite their being typically slow to develop, such smoldering infections lead to repeated flare-ups and are extraordinarily difficult to eradicate. Biofilms have also been implicated in periodontal disease, prostate infections, kidney stones, tuberculosis, Legionnaire's disease and some infections of the middle ear.

Now that biologists understand how bacterial biofilms form, controlling them with drugs able to target their unique properties should be possible. One could, for example, smother the sticky appendages on the surface of the cells with a molecule that

LUSH BIOFILM appeared on an industrial heat exchanger. Such contamination can reduce efficiency.

CAUSE OF CORROSION

Some biofilms cause serious trouble for industry when they establish colonies inside metal piping and hasten corrosion, a process that accounts for half of the forced outages at steam-driven electric power plants. Companies spend billions of dollars every year combating such problems.

WATER WASTERS

The safety of drinking-water supplies can be compromised by biofilms, which often grow inside distribution pipes. Protected by a gooey film, disease-causing microorganisms can proliferate despite chlorination. Researchers at Stanford University have shown, for example, that by forming itself into a biofilm, the organism responsible for outbreaks of cholera, *Vibrio cholerae,* can survive chlorine concentrations 10 to 20 times higher than are normally used to treat drinking water. In 1996 biofilms repeatedly caused the water supply of Washington, D.C., to violate federal standards for bacterial contamination.

readily attaches to them, reducing their ability to bind to surfaces and form a biofilm in the first place. Another option is to interfere with the synthesis of the extracellular matrix, such as by coating medical implants with chemicals that switch off the genes responsible for matrix production. One might also target the molecules that biofilm bacteria use to communicate, thereby halting biofilm formation or suppressing toxin production or other equally invidious activities. That is, instead of trying to overwhelm the offending organisms with poisons (and accidentally killing many more harmless or beneficial bacteria in the process), scientists will soon be able to manipulate the cells in more subtle ways to block their damaging activity.

Tactical Warfare

INDEED, COMMERCIAL development of at least one novel drug has already begun. Staffan Kjelleberg and Peter Steinberg of the University of New South Wales in Sydney, Australia, noted in 1995 that the fronds of a red alga (*Delisea pulchra*) growing in Botany Bay are rarely covered with biofilms. Despite the thousands of bacterial species thriving in these waters, the algal specimens all remain immaculate. How do they do it? Kjelleberg and Steinberg have determined that *D. pulchra* uses chemicals called substituted furanones to keep free of biofilms. The researchers and their university have now launched a company, Biosignal, to produce protective coatings that incorporate substituted furanones, for application to ship hulls and aquaculture equipment.

In the past few years, researchers have gained exciting insights into how the substituted furanones isolated by Kjelleberg and Steinberg work. These substances turn out to be similar to two classes of bacterial molecules: to the acylated homoserine lactones that many biofilm-making bacteria use for quorum sensing and to a class of molecules, newly described by Bonnie L. Bassler of Princeton University, that virtually all bacteria emit to convey signals between different species. Apparently the substituted furanones bind to bacterial cells at the sites normally used by the other signals and thus block the signaling molecules from delivering biofilm-promoting messages.

Indications are that substituted furanones can both prevent biofilm formation and help to break up existing films. They also seem ideal for medical use because they are nontoxic and relatively stable in the body. Moreover, furanones have been present in oceans for millions of years without inducing bacteria to become resistant to their effects—which raises hope that they will be unable to engender resistance in bacteria that colonize medical devices and human tissues.

This line of research is also providing what is perhaps a less practical benefit but one that may in the end prove equally important because it revolutionizes conceptions of bacteria. Biologists are now beginning to speak of the formation of bacterial biofilms as a developmental process, borrowing language normally used to describe a growing embryo. Just as a fertilized egg gives rise to varied cell types during fetal development, bacteria, too, differentiate after they alight on a surface. They synthesize communication molecules, reminiscent of the pheromones and hormones of insects and animals, to coordinate the building of microcolonies within a sophisticated architecture. The design allows nutrients to flow in and wastes to flow out, inviting comparison to the circulatory systems of higher organisms. In some biofilms, bacteria of many species cooperate to digest nutrients that a single type cannot fully exploit. These observations suggest that what most biologists had long viewed as the lowly bacterium may, in fact, occupy a much higher rank in the scheme of life than was ever imagined. SA

MORE TO EXPLORE

Bacterial Biofilms: A Common Cause of Persistent Infections. J. W. Costerton, Philip S. Stewart and E. P. Greenberg in *Science,* Vol. 284, pages 1318–1322; May 21, 1999.

Community Structure and Co-operation in Biofilms. Edited by D. G. Allison, P. Gilbert, H. M. Lappin-Scott and M. Wilson. Cambridge University Press, 2001.

Images and information about biofilms can be found at the Center for Biofilm Engineering at Montana State University at **www.erc.montana.edu**, the American Society for Microbiology at **http://dev.asmusa.org/edusrc/biofilms/** and at the MicrobeLibrary at **www.microbelibrary.org** (search for "biofilm").

MICROGRAPH ON OPPOSITE PAGE: RODNEY DONLAN AND DONALD L. GIBBON *Calgon Corporation;* LICENSED FOR USE, ASM MICROBELIBRARY (www.microbelibrary.org)

IRRESISTIBLE COLOR: Every year some 35 million fish are harvested from coral reefs and exported to aquariums around the world.

Fishy BUSINESS

Cyanide fishing threatens many of the last pristine coral reefs in Southeast Asia. Will an ambitious program to clean up the marine aquarium trade be enough to save them?

Cyanide is one of the fastest-acting poisons known to science. Once ingested, it cripples the body's ability to transport oxygen and begins asphyxiating tissues almost instantly. At higher dosages it slows the heart and even stops electrical activity in the brain. Given cyanide's lethal nature, it is difficult to imagine that squirting the substance at coral-reef fish is a good way to catch them alive. And yet that's common practice in the Philippines and Indonesia, whose collectors supply some 85 percent of the tropical fish that enliven the world's saltwater aquariums.

Disabling agile fish with cyanide makes it easier for divers to capture them before they hide among branches or crevices in the coral, but the consequences are severe. Some experts estimate that half of the poisoned fish die on the reef, and 40 percent of those that survive the initial blast are dead before they reach an aquarium. This startling mortality rate doesn't encompass the devastation to the living corals, invertebrates and nontarget fish in the path of the toxic plume.

Cyanide fishing is only one of several human activities—including poor forestry practices and industrial pollution—that are destroying coral reefs worldwide. But to many marine biologists, cyanide is one of the biggest dangers in Southeast Asian waters. The region harbors nearly 30 percent of the planet's coral reefs and boasts the greatest diversity of marine life anywhere—at least for now. According to two regional surveys published last year, only 4.3 percent of Philippine reefs and only 6.7 percent of those in Indonesia are still in excellent condition. And it is those reefs that live-fish collectors typically target.

BY SARAH SIMPSON • Photographs by Gary Braasch

For nearly 20 years, efforts to reform destructive aspects of the aquarium trade have fallen primarily on the shoulders of the export countries, with limited success as a result. Now a new strategy is placing more opportunity for reef preservation in the hands of importers, retailers and consumers along the trade route. In an ambitious campaign that could help save some of Southeast Asia's last pristine reefs, an international nonprofit organization called the Marine Aquarium Council (MAC) is developing a method for guaranteeing that the marine fish sold in pet stores are collected in an eco-friendly manner. By this fall MAC officials expect to have the first "certified" fish for sale in the U.S.

"There has never been a system to define, identify and verify environmentally sound practices and products in this industry," says the council's executive director, Paul Holthus. "We are also labeling these products so that the consumers can reward those who are responsible."

Because only a handful of the prized fish species can be raised in captivity, the fate of the aquarium hobby lies in preserving the reefs. Aquarium owners know this, Holthus explains, and that is why he believes they will demand certified fish—if given the choice. Even today retailers have no way of knowing the exact origins of the fish they buy from importers. For most of the history of the aquarium trade, people's choices have been limited by scant scientific evidence and by conflicting anecdotes about the severity and exact locations of cyanide use and other destructive activities.

Tainted from the Start

CYANIDE USE in catching aquarium fish goes back nearly to the origins of the industry in 1957, when a Filipino entrepreneur shipped the first live fish to the U.S. in a tin can. Since the early 1960s, aquarium-fish collectors have squirted more than a million kilograms of cyanide onto Philippine reefs, according to estimates by the International Marinelife Alliance (IMA), a nonprofit organization founded in 1985 to fight the spread of destructive fishing practices in the region. Over the past 15 years, the organization has spent $1 million to train fishermen to use hand nets instead of poison. But progress is slow, explains IMA co-founder Vaughan R. Pratt, who directs the organization's operations throughout Southeast Asia. Adequate training can take several months, and until collectors become skilled with hand nets, they can earn more money using cyanide.

When news of cyanide fishing broke in the U.S. in the late 1980s, the gossip among hobbyists was that cyanide was a harmless anesthetic if used in the proper doses, Pratt says. Mortality rates of collected fish were often high, but for the most part aquarium hobbyists chalked that up to the notoriously fragile nature of the fish. Any number of problems along the trade route—poor water quality or too much time enclosed in a plastic bag, for example—can kill fish in transit.

Meanwhile the marine aquarium hobby was flourishing in the U.S. and Europe. Innovations in aquarium technology and animal husbandry were improving people's ability to maintain diversified tanks. This success boosted demand not only for fish but also for corals, anemones and other live reef species. According to a 1999 report by the South Pacific Forum Secretariat, an estimated 700,000 American households were keeping marine aquariums by 1992—a 60 percent rise in two years.

In the face of this increased demand for live fish—and because many Philippine reefs had been destroyed—cyanide fishing had spread to the northernmost island of Indonesia by the early 1990s. The most recent observations of IMA workers implicate nearby Vietnam and Kiribati as well [*see box at left*].

For decades, reef-conservation workers on the front lines in the Philippines did not have the cooperation of the import countries to back their efforts. That is exactly what the Marine Aquarium Council has to offer. This past spring a

Exporters of Marine Aquarium Fish

ABOUT 85 PERCENT of the world export of marine aquarium species comes from the Philippines and Indonesia. Together these two countries also make Southeast Asia the world leader in cyanide use for the collection of live fish. The practice originated with the Philippine aquarium trade in the early 1960s and spread to northern Indonesia in the early 1990s.

CYANIDE USE
- CONFIRMED
- SUSPECTED
- NONE

1 PHILIPPINES
2 INDONESIA
3 VIETNAM
4 KIRIBATI
5 AUSTRALIA
6 PAPUA NEW GUINEA
7 FIJI
8 VANUATU
9 SOLOMON ISLANDS
10 MARSHALL ISLANDS
11 PALAU ISLANDS
12 GUAM

MAP BY LAURIE GRACE; SOURCES: MARINE AQUARIUM COUNCIL, INTERNATIONAL MARINELIFE ALLIANCE

REFORMED CYANIDE FISHERMAN near Bagac, Philippines, bags his live catch for shipment to an export warehouse in Manila.

60-member MAC committee made up of representatives from industry, conservation, government agencies and academia outlined standards for managing the fish and the reefs in a sustainable way. The idea is to forge a reliable chain of custody in which fish are handled appropriately at each step of the trade route, from reef to retailer. One team is spending the summer motivating a string of collectors and exporters in the Philippines to comply with MAC standards, and another group is soliciting support from importers and retailers in the U.S.

Forging an Unbroken Chain

A PROMISING POINT of origin for a certifiable trade route is the city of Bagac, about 90 miles west of Manila. This community of some 21,000 residents lies nestled between the South China Sea and the checkerboard pattern of bright green rice paddies along the flanks of Mount Bataan.

Of the city's 2,500 fishermen, perhaps 30 are aquarium-fish collectors who live with their families in a beachfront cluster of thatch and wood buildings. This group of men (only men fish here) has been collecting fish without cyanide for the past seven years. Before that, cyanide fishing was all they knew. The turning point for them was meeting IMA's

Half of the fish squirted with sodium cyanide typically die on the reef, and **40 percent** of those that survive the initial blast won't live to see an aquarium.

Philippines field director Ferdinand Cruz.

Cruz, who is also a member of MAC, knows the aquarium trade in the Philippines as well as anyone. He was drawn to the fishing communities shortly after he and his sister and mother opened an aquarium-fish export business in Manila in 1984. Almost immediately the family was perplexed by the high death rate of the fish. "We thought our facility was at fault at first," Cruz recalls. When he visited his collectors, they hid their cyanide because it was illegal. Those who admitted to using the poison reasoned that the practice was a harmless way to catch fish alive.

Cruz wasn't convinced. He went out in the boats with the cyanide users and saw dead fish floating in buckets, dead fish on the seafloor and fish convulsing after being squirted. "Six months later I noticed that reefs that had been sprayed were dying and full of algae," he says. "I kept going back to the areas where cyanide was used and made my own opinion that it was a very damaging chemical" [see "How Cyanide Kills," on the next page].

Cruz worked for several years trying to keep his export warehouse cyanide-free, but he finally deemed that goal impossible to achieve. In 1993 he decided to abandon the business and began to work full-time for IMA. Since then, he has helped train some 2,500 of the estimated

How Cyanide Kills

ALTHOUGH THE INTENTION of cyanide-wielding fish collectors is merely to stun their targets, the technique gives new meaning to the word "overkill." The most harrowing estimates suggest that half of the poisoned fish die on the reef, and many more die of health complications before they reach an aquarium.

Divers typically crush one or two white tablets of sodium cyanide into a plastic squeeze bottle. They then squirt the milky fluid—dissolved hydrogen cyanide and particles of the tablets—directly into the corals where the fish hide. The animals within reach of the plume ingest the cyanide ions through their mouths or the soft membranes of their gills. Once inside the fishes' bodies, the poison instantly begins disabling enzymes such as cytochrome oxidase, which accounts for significant oxygen uptake in living cells. The resulting asphyxiation stuns some fish and sends others into spasms, making them easy to grab by hand or net.

The poison tends to accumulate in the blood-rich liver, but studies conducted on freshwater fish also reveal acute damage to the spleen, heart and brain. Researchers point out that marine fish retain fluids in their bodies longer than their freshwater cousins do, giving cyanide more time to do harm before it is metabolized and excreted. Hydrogen cyanide concentrations of five milligrams per liter have proved lethal to certain fish—an exceedingly weak dosage considering that the Nature Conservancy seized cyanide bottles in 1998 that contained concentrations greater than 1,500 milligrams per liter.

Most evidence of cyanide damage to corals is anecdotal, but a handful of scientific studies show that these animals don't fare much better than the fish. Marine biologist James M. Cervino, now a doctoral candidate at the University of South Carolina, witnessed destruction of corals in Southeast Asia when he was working with the Global Coral Reef Alliance, a nonprofit group based in Chappaqua, N.Y. During six years of fieldwork, Cervino grew tired of hearing people claim that cyanide does not kill corals; in response, he set out to garner laboratory evidence of the poison's ill effects.

In a series of experiments completed last year, Cervino exposed 10 species of coral to cyanide concentrations thousands of times lower than those that cyanide fishermen use. Eight of the coral species died immediately; the other two died within three months. The worst news was that the *Acropora* and other branching corals—the most important reef builders—were the most vulnerable. "If you're a little fish, you're going to hide among the branching corals," Cervino points out—which means that fish collectors will squirt those corals more often.

The cyanide disrupted the symbiotic relation between the coral host and its zooxanthellae. These algae give the coral animals their vibrant color, nourish them via photosynthesis and convert their waste into amino acids. Even the lowest cyanide dose (only 50 milligrams per liter) caused the zooxanthellae to erupt out of the corals in a glob of mucus, a process known as bleaching. And although the nonbranching corals proved more resistant to the poison, Cervino says, their outer tissues eventually began sloughing off like the skin of a burn victim.

RIGHT WAY TO FISH: A diver uses a hand net to trap fish that he herds into a large barrier net, which hangs just above the heads of coral.

WRONG WAY TO FISH: A diver simulates the technique of cyanide fishing by using a squeeze bottle filled with milk, which is harmless to the blue tang fish and staghorn coral in the vicinity.

4,000 aquarium-fish collectors in the Philippines. Cruz teaches them to set up barrier nets in canyons or deep fissures between coral heads and then herd the fish toward the net. Like most collectors in Southeast Asia, those in the Philippines breathe underwater through long, flexible plastic hoses called hookahs, which typically deliver air from an old compressor on board the fisherman's canoe. The diver holds the hookah in his teeth and often uses the bubbles from his exhalations to flush fish out of crevices in the coral and into the waiting nets.

Trained net fishermen are critical to a sustainable aquarium trade, but exporters also play a key role in MAC's plan. Most of the exporters, who constitute the next step in the chain of custody, are based in Manila. There, in warehouses filled with tanks, new arrivals typically mix with fish collected elsewhere around the country, many of them with cyanide. To make certification work, export warehouses will be required to quarantine fish that come from certified collectors.

At the warehouses, some fish can also be tested for cyanide exposure. Thanks in part to the efforts of Pratt and other IMA workers, cyanide detection laboratories are already in place. In 1991 the Philippines Bureau of Fisheries and Aquatic Resources contracted IMA to begin testing random samples of confiscated fish. The first detection laboratory opened near the Manila airport in 1991, and by early this year six laboratories around the country had tested more than 32,000 fish.

No current test can detect cyanide in living fish, so an unlucky few must be sacrificed. Chemists inspect and weigh each fish and liquefy it in a blender. The fish mush is distilled in a strong, hot acid so that any cyanide is liberated as hydrogen cyanide gas and then absorbed by a solution of sodium hydroxide. Electrode probes select for cyanide ions in the solution, enabling technicians to calculate cyanide levels in parts per million. Between 1996 and 1999, for example, workers saw the proportion of cyanide-tainted fish drop from 43 to 8 percent—a sign that IMA's investments are paying off.

Based on the considerable challenges of forging a certifiable chain of custody in the Philippines, Holthus says, the standards should be easy to maintain in Hawaii, Australia and other regions that already have high-quality operations in place. Once a chain of custody is certifiable in the export countries, it's up to importers and retailers in the U.S. to choose to buy those certified fish—and to live up to the MAC guidelines for their own handling practices. Even with the cooperation of importers, turning the poison tide in Indonesia, where fewer collectors are properly trained, will not be as easy. "If certification fails or only half-succeeds in the Philippines," Cruz cautions, "MAC standards will not take off in Indonesia."

Peter J. Rubec, who co-founded IMA with Pratt and works as a fisheries biologist with the Florida Marine Research Institute in St. Petersburg, hopes that the efforts of IMA and MAC will "provide the scientific evidence needed to convince the industry that net-caught fish are a viable economic alternative to cyanide-caught fish." Some retailers aren't so sure. "The pressure in the marketplace today is for lower prices, not higher ones," says James A. Bennett, owner of an aquarium retail store in Portland, Ore. "If MAC's plan increases the cost of the fish, that's not going to work."

Holthus hopes that certification will not actually cost the consumer any more. If the system works, he says, then the money saved by reducing fish mortality could offset any increased costs of certification. The MAC standards require that no more than 1 percent of each species die at any given point in the chain of custody. Achieving this goal, Rubec believes, would be a tremendous feat. He estimates that at least 10 percent of cyanide-caught fish die at each step in the trade route.

What is more, the fish grow considerably in value from one end of the trade route to the other. An orange-and-white-striped clownfish bought from a Filipino collector for about 10 cents, for instance, will sell for $25 or more in an American pet store. With that kind of markup, Rubec and others argue that the industry should be able to absorb the remaining additional costs of certification.

Not Soon Enough for Some

ONLY TIME WILL TELL whether economic obstacles will stymie MAC's mission. A few certified fish will be available to certain U.S. consumers this fall, but it may take a while for the desires of the market to force the aquarium trade to comply with the MAC standards. For some reef experts, the wait is agonizing.

"I don't think the Marine Aquarium Council has been tough enough," says marine biologist James M. Cervino, now a doctoral candidate at the University of South Carolina. After seeing cyanide damage for himself during his six years of service with the Global Coral Reef Alliance, Cervino argues that the trade should be halted temporarily: "If you don't have evidence that your fish were caught in a sustainable way, I can't see [this trade] being allowed to continue."

International law already bans the trade of thousands of species of stony coral under the Convention on the International Trade in Endangered Species of Wild Fauna and Flora (CITES), but most of the coral-reef animals in the aquarium trade are not listed. Some local village governments in the Philippines have experimented with export bans on certain live reef species, but Cruz says that the restrictions just drove the fishermen to oth-

About 2,500 of the Philippines's estimated **4,000 cyanide fishers** who work in the aquarium trade have been trained to **use hand nets** instead of poison.

er illegal activities. He has been campaigning for local governments to grant fishing licenses as an alternative way to regulate collection. "If this trade does not prove to be sustainable, then it will have to close completely," Cruz warns. "In the meantime, we should still use the resources the right way so that the community can profit from it."

After a certification system is up and running, import restrictions in the U.S. could tighten the loop. Last fall the U.S. Coral Reef Task Force, established by an executive order in 1998, helped to draft legislation that would ensure that consumer demand for marine aquarium organisms does not contribute to the degradation of reefs and their inhabitants, as it does today, says task-force member Barbara A. Best. The trade recommendations, which were still being considered by Congress in mid-May, reflect MAC's philosophy that certification is a way to encourage responsible and sustainable trade. The legislation also provides that after an unspecified period of time, the U.S. should ban the import of any coral-reef species unless it is accompanied by official documentation that the animal was not collected through the use of destructive fishing practices.

"Industry-certification schemes can be quite slow in catching on, and legislation

The number of **fish testing positive** for cyanide exposure in the Philippines **dropped** from 43 to 8 percent between 1996 and 1999—a sign that reform efforts are working.

that required certification would speed up the process," explains Best, who also advises the U.S. Agency for International Development on marine resource and policy issues. "I have had some retailers tell me that they view the trade recommendations as one way to ensure that everyone carries animals that are being collected sustainably and treated humanely," Best says. "This would also ensure that those retailers that are behaving responsibly and carrying certified products are not undermined by lower prices from other retailers."

"I would adapt, because all of my competitors would have to do the same," says Bennett, who has seriously considered eliminating sales of live marine fish from his Portland aquarium store. "Some of us would invest a lot of money in a hurry and try to farm these things."

Even with legislative restrictions and a strong consumer demand for certified fish working in tandem, coral reefs in certain export countries may still be at risk. Indeed, the first MAC-certified fish may not actually be cyanide-free. A few tainted fish

POISON CONTROL: Fish confiscated from an export warehouse in Manila await testing for cyanide exposure. Clockwise from upper right: unidentified, spot-banded butterflyfish, regal angelfish, redtooth triggerfish, forcepsfish, herald's angelfish, unidentified damselfish, keyhole angelfish, pyramid butterflyfish and redfin wrasse.

may slip through this initial testing phase of MAC's long-term plan, in which the standards are intentionally basic so that they can be met relatively quickly. "We'll raise the bar as we go along," Holthus says. During the next two years, MAC will design more detailed standards, and the organization will monitor the health of the reefs as the changes take place.

Even if MAC's certification works to curtail cyanide use among aquarium-fish collectors, some researchers worry that there is still no guarantee that fish collection will not degrade the reefs. A case in point is Kona, Hawaii. Although aquarium-fish collectors do not use cyanide in this area, Brian N. Tissot of Washington State University in Vancouver, Wash., and Leon E. Hallacher of the University of Hawaii at Hilo discovered in late 1999 that the collectors' activities were stunting the populations of seven species of coral-reef fishes, three of which are herbivores. Without these grazing fish to keep algae in check, the prolific plants could eventually suffocate the coral animals.

Another challenge is reducing destructive practices among collectors of live food fish, who have spread cyanide use into Malaysia, the Marshall Islands, Papua New Guinea and possibly other areas of Southeast Asia.

Cruz and other IMA officials have reported that these fishermen often make forays into coastal areas where they have little interest in the long-term productivity of the reefs. Aquarium-fish collectors, on the other hand, are mainly people from local communities that have been relying on the same reefs for their livelihoods for generations. In part on Cruz's recommendation, MAC's certification standards require that local fishermen protect their own turf, even if that means patrolling coastal waters and chasing outsiders away—a practice that Cruz has already helped implement in several Filipino villages.

Creating strong incentives for local fishermen to be responsible for managing their own reefs "is probably the best hope in most of these areas for ever conserving the reefs," Holthus says. He has also seen growing interest among certain players in the live food fish trade to set up their own certification scheme. Better still, reefs might be developed into tourist areas for divers or protected parks where no fishing is allowed. But because of economic and political barriers, only a small number of reefs will ever fall into these categories.

The bottom line according to Cruz: If cyanide fishing isn't stopped, a lot of these reefs will be gone in a few decades. The good news, he believes, is that the battle against cyanide use in the Philippines is no longer uphill. SA

Sarah Simpson is a staff editor and writer. Additional reporting by Gary Braasch.

Ways to Stop Cyanide Fishing

Anyone who wants to argue that cyanide fishing does not damage coral reefs should consider one important fact: the practice is forbidden in most of Southeast Asia. In 1975 a presidential decree in the Philippines made it illegal to fish with cyanide, possess it on a boat or sell fish caught with it, and Indonesia followed suit 10 years later. But cyanide still has several legitimate uses in industry—extracting gold from ore, for example—so the poison's importation is not strictly regulated. Clever criminals, along with government corruption and political strife, make enforcement extraordinarily difficult. That's why the International Marinelife Alliance, the Marine Aquarium Council and dozens of other organizations are pursuing a variety of strategies to halt this lethal—and illicit—practice.

GLOVED CHEMIST weighs a dead redfin wrasse at a cyanide detection laboratory that has operated in Manila since 1991.

1. Confiscate random samples of live fish from export warehouses and test them for cyanide exposure.
2. Train aquarium fishers to use proper collecting techniques: hand nets rather than poison or other chemicals.
3. Label fish that were caught without cyanide so that fish buyers can choose to support practices that preserve the reefs.
4. Encourage fishing communities to keep foreign fishers and illegal activities out of their local waters.
5. License aquarium collectors in export countries in order to limit their effects on the reefs.
6. Restrict the import of live coral-reef species that are not accompanied by documentation that they were captured without poison.

MORE TO EXPLORE

Poison and Profit: Cyanide Fishing in the Indo-Pacific. Charles Victor Barber and Vaughan Pratt in *Environment,* Vol. 40, No. 8, pages 5–34; October 1998. Also available at **www.imamarinelife.org/environment.htm**

Cyanide-free, Net-caught Fish for the Marine Aquarium Trade. Peter J. Rubec et al. in *Aquarium Sciences and Conservation.* Chapman and Hall (in press). Condensed version available at **www.spc.org.nc/coastfish/news/lrf/7/LRF7-08.htm**

Marine Aquarium Council, **www.aquariumcouncil.org/**

International Marinelife Alliance, **www.imamarinelife.org/**

U.S. Coral Reef Task Force, **http://coralreef.gov/**

SUNSCREEN

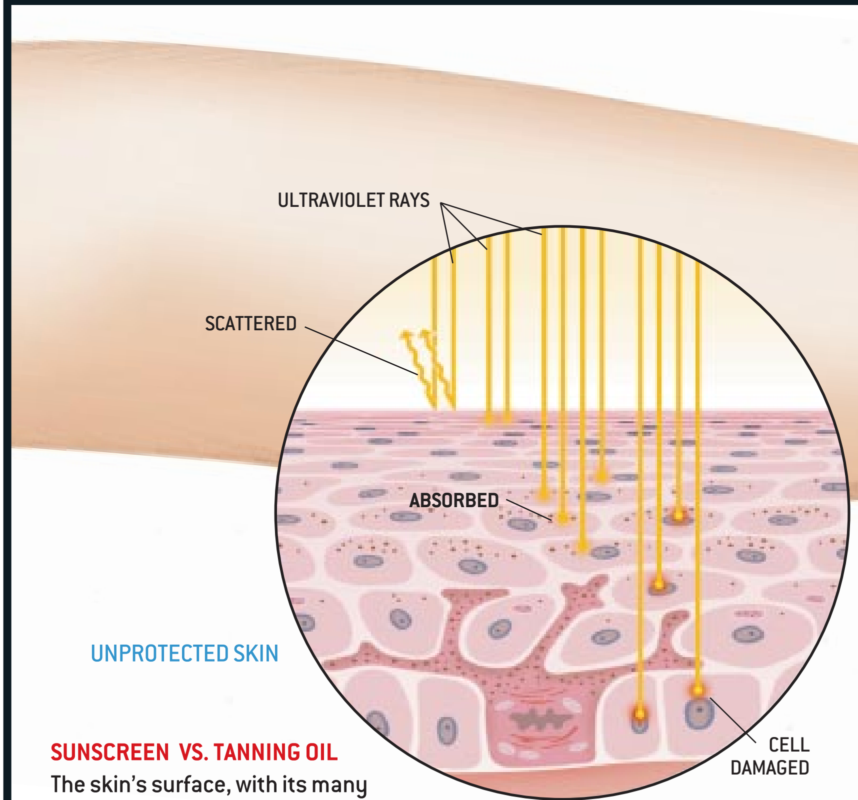
Tan or Burn

While protecting your body, skin must protect itself from the sun's ultraviolet radiation, which can cause premature aging and cancers. Sunscreens can help. Sunburn occurs when strong UV rays harm cells in the skin's outermost layer, the epidermis. Blood vessels in deeper layers dilate, turning the skin red: a sunburn. Regular exposure causes the epidermis to produce more melanin pigment in an attempt to absorb UV rays. If enough melanin accumulates, the skin darkens: a tan. Dark-skinned people have more melanin than light-skinned people and so don't burn as readily.

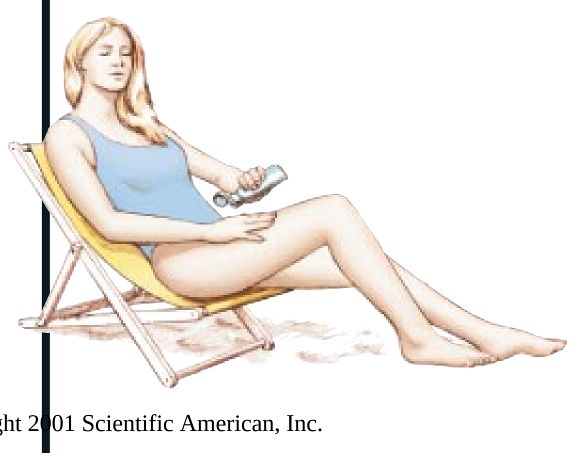
Active chemicals in sunscreen also filter UV rays, slowing injury and thus the sunburn and tanning reactions. Sunscreens are labeled with an SPF, or sun protection factor—a relative rating standardized by the FDA. Say that skin begins to burn after 10 minutes of exposure. When it is protected by an SPF 15 sunscreen, a comparable burn will take 15 times as long. An SPF 30 sunscreen will slow the burn for 30 times as long. But don't get cocky. Labs rate sunscreens on human subjects at a density of two milligrams per square centimeter, according to J. Frank Nash, a principal scientist at Procter & Gamble. Yet a typical beachgoer lathers up at perhaps half that concentration, halving protection. And Nash says no compound can fully stop UV penetration; there's no such thing as sunblock.

You can also discount claims about antioxidant vitamins E and C. Oxidation accounts for only a few percent of the UV damage, notes dermatologist Barbara A. Gilchrest of the Boston University School of Medicine, and "there's no good evidence" that vitamins in topical products can even enter the skin in active form. More worry comes from the fact that sunscreens primarily filter the shorter, or UVB, ultraviolet wavelengths, yet recent studies show that the longer (UVA) rays may contribute more to skin aging than previously thought.

So what's the best sunscreen? A thick shirt. And because cell damage is cumulative, experts recommend daily use of sunscreen, or of moisturizers with sunscreen, on areas such as the hands and face. A one-hour exposure every day for five days could be as threatening as one long day at the beach. *—Mark Fischetti*



SUNSCREEN VS. TANNING OIL
The skin's surface, with its many micropeaks and valleys, scatters a small number of the sun's ultraviolet rays. Most of the rays penetrate the epidermis. Melanin absorbs many of these photons, but some of the remainder injure DNA in the living cells. This damage signals capillaries in the dermis to dilate, increasing blood content and producing redness, or sunburn. Sunscreen acts as a filter that absorbs additional UV rays, dissipating their energy. Tanning oil smooths the surface, so fewer rays scatter and more penetrate, speeding sunburn or tanning.



ILLUSTRATIONS BY GEORGE RETSECK

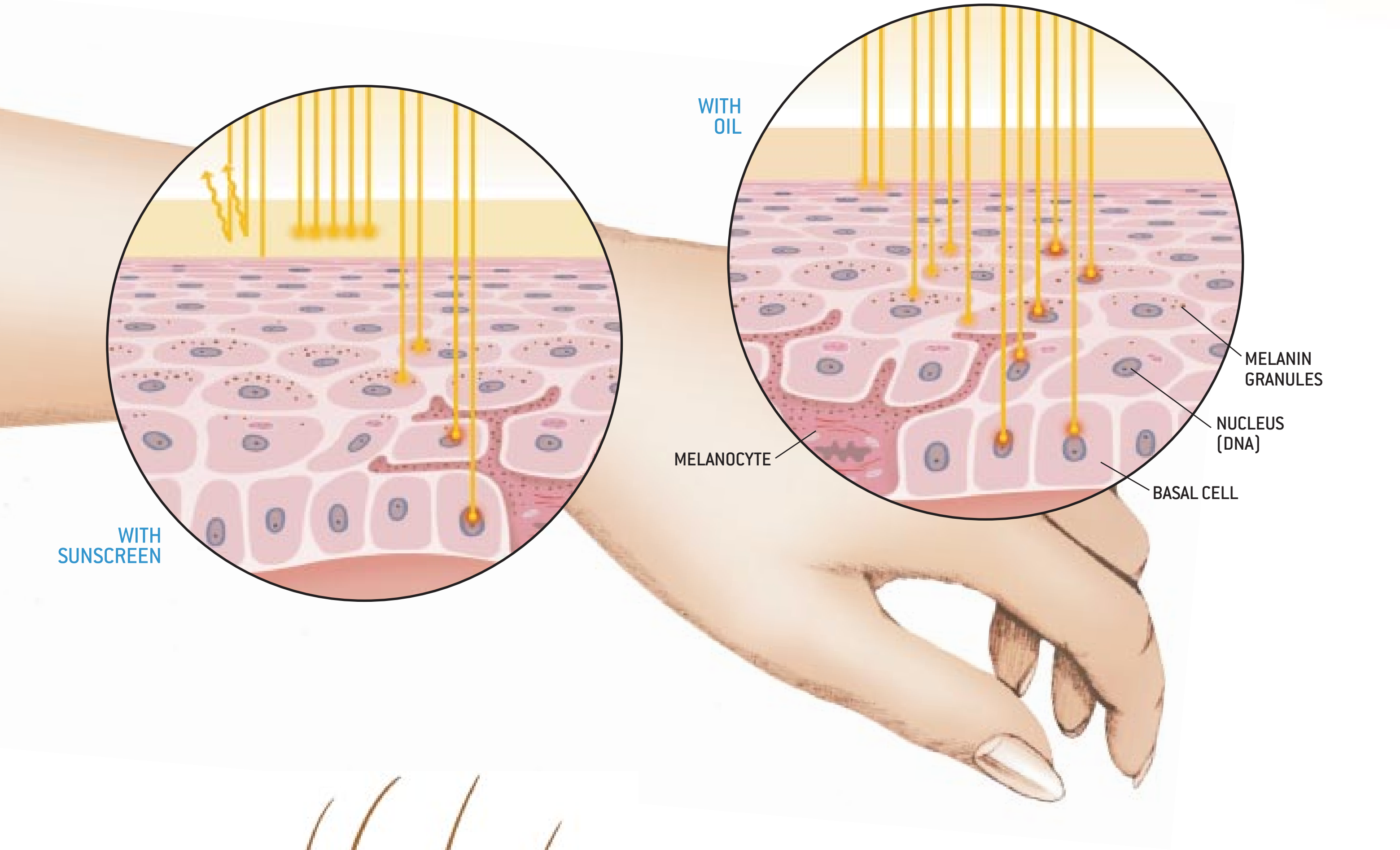
DID YOU KNOW . . .

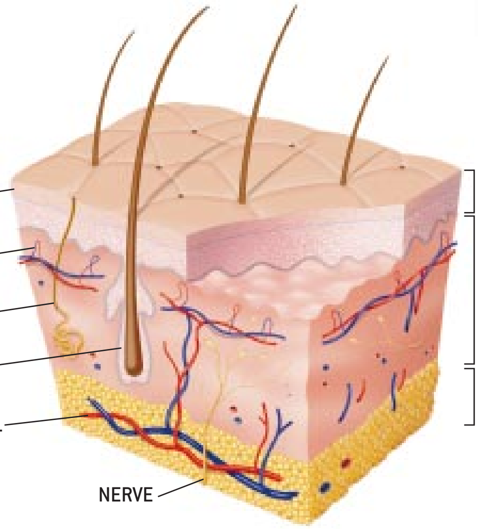
➤ PABA-FREE For decades sunscreen makers used para-aminobenzoic acid (PABA) as an active ingredient. But it stains clothes and causes an allergic reaction in 5 percent of the population, and controversial evidence suggests it might be carcinogenic. Today many brands shout out "PABA-free."

➤ YOUR EPIDERMIS IS SHOWING Melanin, the epidermis pigment that absorbs ultraviolet rays, also absorbs visible light. The more eumelanin (brown pigment) you have, the darker your skin color, from white to black. Redheads produce relatively more phaeomelanin (red and yellow), a poorer UV absorber, so they are more likely to sunburn and less likely to tan. Albinos have no melanin and are at great risk in the sun.

➤ TRUCKER'S ELBOW Glass absorbs UV rays very effectively, so you can grip your car's steering wheel for hours in baking heat and not sunburn your hands or arms. But roll down the window and rest your elbow on the ledge, and you might arrive with a telltale burn truckers know well.

➤ TAN IN A BOTTLE "Sunless" tanning sprays and lotions contain dihydroxyacetone (DHA), which binds to amino acids in the outermost (dead) layer of skin to produce a tan—some more realistic than others. They provide no UV protection, however, so sunscreen is still needed outdoors.





BENEATH THE SURFACE

Two main layers make up the skin. The dermis contains blood vessels and nerves. The epidermis contains melanin, an inert protein that gives skin its color. Melanocytes (*above*) insert melanin granules inside cells as newly formed cells push older ones to the surface. As the cells migrate, they produce keratin, another inert protein, and then die, leaving the keratin to form the tough stratum corneum we see every day. The same keratin also constitutes our hair and nails, as well as the feathers, scales, hooves and claws that adorn eagles, trout, horses and alligators.

The Universe atop a Mountain

GAZING AT THE COSMOS FROM KITT PEAK NATIONAL OBSERVATORY BY MARGUERITE HOLLOWAY

The fog has lifted and the evening air has stolen in, wrapping the mountain and the desert below in a deep chill. Thirteen of us, warmly dressed in layers although it is the middle of spring and the day was hot, are huddled quietly around a small telescope in a drafty observatory, waiting for our view of the cosmos. With a grinding rumble, the roof above us opens and rotates slowly until a slice of night sky and a single bright point have been chosen. One by one we look: Venus, magnified about 130 times, appears as a slender, glowing crescent.

As the night darkens, more planets and stars become visible, despite the bleaching glow of a full moon. We see Jupiter's cloud bands—faint pink, like the inside of a lady slipper shell—and two of its moons, the binary star Castor, many star clusters, the blinding face of our disruptive moon, some of the stars in the Trapezium of the wispy Orion Nebula, and a spiral galaxy. For several hours we watch the sky change as Earth turns. And twice we look at Saturn, unreal in its beautiful perfection, so solid and at the same time so delicate. "This is pretty much the best object in the sky," says Flynn Haase, an amateur astronomer and this evening's guide. "I usually keep it as the finale object."

Haase is one of the leaders of the Nightly Observing Program at Kitt Peak National Observatory, which sits in the Quinlan Mountains on the Tohono O'odham Reservation in southwestern Arizona. Nearly every evening as many as 20 people can observe the night sky through a 0.4-meter telescope at the same time that astronomers from all over the

KITT PEAK is where dark matter and the first gravitational lens—in which one galaxy bends light from a more distant one—were discovered.

DANNY LEHMAN Corbis

world are going to work at the much larger telescopes around the mountaintop. With 24 telescopes—the biggest of which, the Mayall, measures four meters across—Kitt Peak has the largest collection of optical telescopes in the world. Some of them can be visited during the day, when the professional astronomers are asleep.

It is an eerie place, the top of this 6,875-foot mountain. Quiet in the daytime because of the nocturnal researchers, quiet and pitch-black in the nighttime because unwanted light or vibrations from noise can throw off the precise measurements and obscure the clear views needed to study the sky. The telescopes, most of them housed in white observatories, cover the mountaintop like the buildings of some luminous futuristic city. The Mayall, used to study dark matter and the large-scale structure of the universe, stands on the highest promontory. Spread below it on the 200 or so acres of the summit are the 2.1-meter telescope that discerned the first pulsating white dwarf, the 3.5-meter WIYN telescope, which sits in an octagonal building that is freely ventilated to remove the image-distorting heat of the day, and the McMath-Pierce Solar Telescope Facility, where the world's largest solar telescope is found.

The telescopes of Kitt Peak have contributed profoundly to our understanding of space. "But mostly it is not new things being discovered," explains Haase, who also works at several of the telescopes. "Mostly it is to further understand things, to get the data to back up the ideas that they have already come up with in the lab." Two of the telescopes are used for the Spacewatch program: they scan the heavens for asteroids and in recent years have identified a few near-miss candidates hurtling toward us. All of this work is done under the auspices of the Association of Universities for Research in Astronomy, which, in turn, is under contract with the National Science Foundation. Twenty-nine universities conduct research on site, and twice a year astronomers submit competitive proposals for a chance to work here—some may have to wait a year or two before they can come to gather data.

The public, however, is free to wander the grounds and in and out of three observatories. From the viewing room next to the 2.1-meter mirror, you sense the massiveness of the machinery needed to move the 60 tons of optical equipment, and you can see the small room behind the telescope where the astronomers sit at their computers, downloading data.

VOYAGES

In the McMath-Pierce solar telescope observation room, you can look down the 135-meter shaft that runs parallel to Earth's axis and see the different mirrors that ultimately resolve the image of the sun to one that is about a meter wide, easy for astronomical study.

Although the equipment is impressive and the tours informative, it is hard to get a sense of how the real work of astronomers is conducted. But at the Nightly Observing Program, you can at least experience how most astronomers used to work—with the naked eye—and can understand why the vast, mysterious beauty of the cosmos drives them to build silent, domed cities on the top of mountains in the middle of deserts.

The observatory is open to visitors most every day from 9 A.M. until 3:45 P.M., and guided tours (for $2) are offered at 10 A.M., 11:30 A.M. and 1:30 P.M. The 56-mile-or-so drive to Kitt Peak takes about an hour and a half from Tucson. The easiest route is I-10 to I-19 to Route 86. But the more beautiful route—especially when it is spring and the desert is in full, fragrant bloom—is west through the surreal, saguaro-studded Tucson Mountain Park and then down Kinney Road to Route 86. Further information about Kitt Peak can be found at www.noao.edu/kpno/

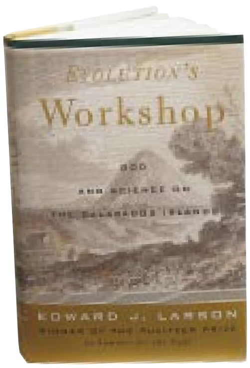
McMATH-PIERCE solar telescope's optical shaft runs underground, parallel to the axis of Earth.

JAMES MARSHALL *Corbis*

For more information about the Nightly Observing Program, which begins 45 minutes after sunset, go to www.noao.edu/outreach/nop/ or call 520-318-8726 well in advance for reservations (there are about 4,500 visitors a year). The cost is $35 for adults; $25 for children, students and seniors. The drive back to Tucson from Kitt Peak when it is dark can be as chilling as the night air, so be careful: the road through the Sonoran Desert is lined with crosses and altars marking the sites of fatal car accidents. SA

Our Evolving View of the Galápagos

THE FAMOUS ISLANDS BEFORE AND AFTER CHARLES DARWIN **BY RICHARD MILNER**



EVOLUTION'S WORKSHOP: GOD AND SCIENCE ON THE GALÁPAGOS ISLANDS
by Edward J. Larson
Basic Books, New York, 2001 ($27.50)

A few hundred years ago the bleak, inhospitable oceanic islands known as the Galápagos archipelago were visited only by buccaneers and, later, by whalers and sealers who fed their crews on its giant tortoises. By the mid-19th century, however, these volcanic cones—located 600 miles west of Ecuador on the equator—began to attract such distinguished visitors as Herman Melville, Charles Darwin and Louis Agassiz. Now historian Edward J. Larson, author of the Pulitzer Prize–winning *Summer for the Gods* (an account of the Scopes trial), invites us to witness the entertaining parade of Galápagos pirates, adventurers, eccentrics, naturalists and other scientists who changed this extraordinary place and were changed by it.

For novelist Melville, who sailed there during the 1840s, the Galápagos appeared to be "evilly enchanted ground," a Dantean purgatory populated by vile, hissing reptiles. Young Darwin, on the other hand, landing in 1835, thought the islands looked primeval rather than hellish: "We seem to be brought somewhat near to . . . that mystery of mysteries—the first appearance of new beings on this earth." As Larson reminds us, it was only later, back in London, that Darwin nurtured his heretical conclusion that the distribution of Galápagos creatures and their possible relationship to mainland ancestors "would undermine the stability of species."

Harvard zoologist Louis Agassiz, an opponent of evolution, had still another take on the Galápagos. Perceiving no "struggle for existence" when he and his wife visited there in 1872, Agassiz found the island creatures wonderfully fearless, exhibiting a "delight in living" wrought by a beneficent Creator. After millennia with no large ground predators, the animals were indeed naive, but Darwin predicted that they would soon become afraid of humans. (I've always wondered why they have not. After centuries of predation by people, where are all the shy, timid whales, tortoises, birds and seals that selection ought to have produced? Or has there simply not been enough time?)

Major museums launched expeditions to the archipelago, and Larson introduces us to the rapacious world of collectors, along with body counts of the island wildlife they prized. Seven scientific expeditions, all from the San Francisco Bay Area, invaded the Galápagos between 1897 and 1906. The last of them took 75,000 specimens, including 264 tortoises from 10 different islands. I find it remarkable, after reading Larson's account, that any Galápagos wildlife at all managed to survive the attentions of the scientific community.

By the 1960s, with the establishment of the Charles Darwin Research Station and the conferral of national park status by Ecuador, the Galápagos entered its present phase of conservation and observation. Ornithologists Peter and Rosemary Grant have spent 30 years watching and measuring Darwin's finches on several tiny islands. Where various species mixed together on the same islands, the Grants found that they ate different foods—evidence for selection by competitive exclusion.

They were even able to watch the finches' beaks evolve. After heavy rains,

DARWIN AND THE BEAGLE, ***Alan Moorehead's 1969 classic in a beautiful new edition from the Adventure Library ($35),*** makes an excellent companion to *Evolution's Workshop.* The handsomely bound and printed edition contains a new introduction by science historian Daniel Kevles and the color plates and black-and-white illustrations from the original—at right is the Galápagos turtledove.

PHOTOGRAPHS BY BETH PHILLIPS

succulent seeds were everywhere, whereas during droughts only tough, hard seeds remained. The Grants proved that half a millimeter of beak could mean the difference between survival and starvation. Unconvinced that this was a demonstration of evolution in action, creationists conceded that the finches might have developed bigger or smaller beaks within a few generations but pointed out that none turned into vultures or ducks!

As for the future, there is good news and bad news. First, the good news: lots of scientists and conservationists are devoting themselves to caring for the Galápagos and learning from it, and more than 2,500 giant tortoises have already been bred and released onto the islands from which they had been plundered. Now the bad news: illegal commercial fishing on a large scale in park waters, a swollen, growing and disgruntled immigrant population of 17,000 from the mainland, and occasional oil spills produce continual crises for the ecosystem.

I am privileged to count among my friends Sarah Darwin, a botanical artist who is also the great-great-granddaughter of Charles. When she visited the Galápagos with her family for the first time in 1996, I asked her to write a postcard to the old boy for the London Natural History Museum's First Annual Galápagos Day. "I sit here in a café on the Avenue de Charles Darwin," she wrote, "watching tourists buy tee-shirts and mugs with your picture on them.... I am sorry to relate, though, that many problems here would sadden you ... and all are caused by human greed or thoughtlessness. It will take a tough, caring international effort to ensure that this place of marvels is not destroyed, but will remain to delight and instruct my own great-great-grandchildren."

Amen, Sarah. SA

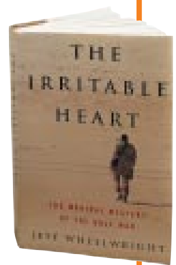
Richard Milner is the author of The Encylopedia of Evolution: Humanity's Search for Its Origins *and* Charles Darwin: Evolution of a Naturalist.

THE EDITORS **RECOMMEND**

THE IRRITABLE HEART: THE MEDICAL MYSTERY OF THE GULF WAR

by Jeff Wheelwright. W. W. Norton, New York, 2001 ($26.95)

One veteran in seven of the 1991 Gulf War suffers from a mysterious condition called Gulf War syndrome—rapid pulse, shortness of breath, fatigue, headache, dizziness and disturbed sleep. Wheelwright, former science editor of *Life,* describes several case histories and the inconclusive studies that have been made of the syndrome. Opinion is divided, he says, between the toxic hypothesis—that the illnesses must spring from hazardous substances that were rife in the theater of war—and the stress hypothesis—that the illnesses were either caused or greatly amplified by psychological stress. The jury is still out.



AN INTIMATE LOOK AT THE NIGHT SKY

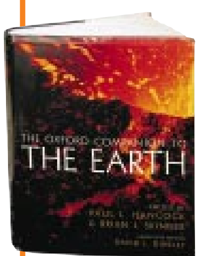
by Chet Raymo. Walker & Company, New York, 2001 ($26)

"We are animals who evolved in a world without artificial light. Our brains were sculpted as much by darkness as by light." Yet today, because there is so much artificial light, many people see little of the stars. Raymo, who teaches astronomy at Stonehill College, seeks to show them what they are missing. He provides star maps for each of the seasons and many spectacular photographs of the night sky. The accompanying text lucidly presents the astronomy: how the stars got there, how they burn and how they die. "This book has as its purpose," Raymo writes, "the reestablishment of intimacy with the night."

THE OXFORD COMPANION TO THE EARTH

edited by Paul L. Hancock and Brian J. Skinner. Oxford University Press, New York, 2001 ($75)

Fat, solid and rewarding, the *Companion* undertakes to give us "concise, readable, friendly, and stimulating accounts of the many phenomena, processes, and natural materials that make the Earth such a dynamic and fascinating planet." It succeeds admirably. From "acid rain," with an excellent explanation of the pH scale, to "zoogeomorphology," the effects that animals have on the surface of the earth, it provides a wealth of clear information. It also offers entries that one might not expect, among them one on references to geology in literature and one on the possible connection between geology and the quality of wine.



OXYGEN: A PLAY IN 2 ACTS

by Carl Djerassi and Roald Hoffmann. Wiley-VCH, New York, 2001 ($14.95)

Although it would be great fun to see *Oxygen* performed, the play makes an entertaining read. Its premise is that the Nobel Foundation, in honor of the centenary of the prize, decides to award a "retro-Nobel" for the discovery of oxygen—but should it go to Antoine Lavoisier, Joseph Priestly or Carl Wilhelm Scheele? The action alternates between 1777 and 2001, the tensions and ambiguities of the 18th century mirrored in the 21st. The play opens in a sauna in Stockholm, where the wives of the three scientists ("their bodies covered to various extents... Mrs. Priestly most decorously and Mme. Lavoisier most daringly") reveal the rivalry among their husbands. *Oxygen* is an imaginative addition to the long list of publications—from the sciences to poetry and fiction—by the distinguished authors. Djerassi is professor of chemistry at Stanford and perhaps best known as the inventor of the birth-control pill. Hoffmann is professor of chemistry at Cornell and a Nobel laureate.

All the books reviewed are available for purchase through www.sciam.com

Seeing Red, Feeling Blue

BY DENNIS E. SHASHA

Here's a puzzle full of clashing colors. Picture a geometric figure that's colored partly red and partly blue. If the figure contains at least one red point and one blue point that are exactly 10 centimeters apart, mathematicians would say—in their wonderfully abstruse jargon—that the figure satisfies the 10-centimeter red-blue bicoloration condition. The idea behind this month's puzzle is to take a simple shape, such as a line segment or a circle, and determine whether every conceivable pattern of red and blue on that figure satisfies the 10-centimeter condition.

As a warm-up, consider line segments. Can you paint a red-and-blue pattern on a line segment that does not satisfy the 10-centimeter condition? Assume that the line segment is one meter long, with the zero-centimeter mark at the left end and the 100-centimeter mark at the right (*illustration A*). Color the following intervals red: 0–1, 9–11, 19–21, 29–31, 39–41, 49–51, 59–61, 69–71, 79–81, 89–91 and 99–100. Now color all the other intervals blue. Notice that every point on this segment will have the same color as the points that are 10 centimeters to its left or right. So this pattern does not satisfy the 10-centimeter condition.

Let's move on to circles. For any circle with a radius of less than 10 centimeters, can you draw a red-and-blue pattern that does not satisfy the 10-centimeter condition? Again, the answer is yes. Simply color the circle's center point blue and the rest of the circle red (*illustration B*). Any point that is 10 centimeters from the blue point at the center will lie outside the circle.

But what about larger circles? For a circle with a radius of 10 centimeters or more, can you draw a red-and-blue pattern that does not satisfy the 10-centimeter rule? And if not, can you prove that no such pattern can exist? A reminder: at least one point in the circle must be colored red, and at least one point must be blue. The solution to the puzzle will appear in next month's column. SA

Answer to Last Month's Puzzle

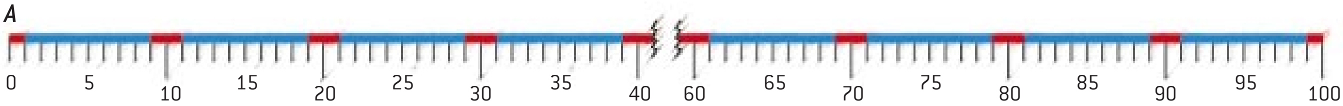
To determine which of the five people is the consistent truth teller, first ask A, "Are you the truth teller?" If the answer is yes, ask A, "Who is the truth teller?" If A points to himself, he is indeed the truth teller, because his answers are consistent. If he points to anyone else, then that person is the truth teller. (In this case, A's answers are inconsistent, so he must have lied the first time. Because A alternately lies and tells the truth, he will answer the second question truthfully.)

If A's answer to the first question is no, then A is telling the truth but is an alternating liar. So ask him, "Who is not the consistent truth teller?" His answer must be a lie, so he will point to the truth teller. This solution works for any number of people.

Web Solution

For a peek at the answer to this month's problem, visit www.sciam.com

A



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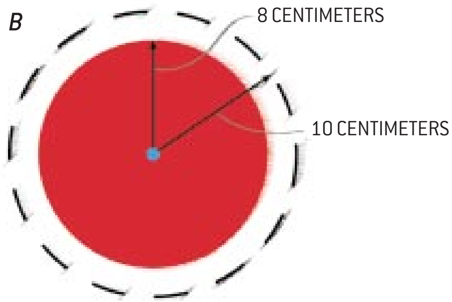

JOHNNY JOHNSON

Out of This World

ONE UFO EXPERT SAYS THAT ALIENS DON'T GET AROUND MUCH ANYMORE. BUT WHAT IF THAT'S JUST WHAT THEY WANT YOU TO THINK? **BY STEVE MIRSKY**

The sun, or perhaps some other star that warms intelligent beings light-years from Earth, has set on a venerable English institution. After half a century of inspired eccentricity, the British Flying Saucer Bureau has closed the pod bay doors. It has ceased to be. It has expired. It is pushing up crop circles. It is an ex-bureau. The reason: the bureau has virtually stopped receiving reports of flying saucers.

A family enterprise, the bureau was the 1953 brainchild of the late Edgar Plunkett and his son Denis (which makes Denis both the bureau's father and brainbrother). At the height of alien activity, the Plunketts fielded some 30 reported sightings a week, and the bureau claimed about 1,500 members scattered around the world, if not beyond. But now no one seems to be reporting UFOs.

According to the *Times* of London, Plunkett believes that the drop-off in close encounters may have a reasonable explanation: perhaps the aliens have completed their survey of Earth. One can sympathize with such an interpretation. My own home, for example, has been blessedly elephant-free lo these many years, clearly the result of some incredibly efficacious antielephant spray. With an abiding faith in Occam's new MACH3 razor—one blade tugs on loopy logic while the second blade cuts it off, leaving the third blade to skate on exceptionally thin ice—I propose other possible explanations for the downturn in UFO reports:

- The aliens have finally perfected their cloaking technology. After all, evidence of absence is not absence of evidence (which is, of course, not evidence of absence). Just because we no longer see the aliens doesn't mean they're not there. Actually, they are there; the skies are lousy with them, they're coco-butting one another's bald, veined, throbbing, giant heads over the best orbits. But until they drop the cloak because they've got some beaming to do, we won't see them.
- Sightings are as frequent as ever; people are merely neglecting to report them. With 401(k)s threatening to leave impact craters, no one is interested in aliens unless Alan Greenspan is one.
- People are still seeing them, but the aliens have administered a mass posthypnotic suggestion: "When you start to think of aliens, immediately switch to thinking about mad cow disease."
- The aliens have cleverly designed their ships to look just like standard commercial aircraft, thus explaining the massive delays at LaGuardia airport. (Newark airport is alien-free, the extraterrestrials having avoided New Jersey since the Grovers Mill snafu of '38.)
- The aliens are indeed gone, but the idea that they could complete their survey of Earth in a mere 50 years is both ludicrous and insulting. In fact, they ran out of alien government funding. Besides, a lot of the aliens back on their home planet thought that the missions to Earth were just a big hoax anyway.

The drop-off in close encounters may have a reasonable explanation: perhaps the aliens have completed their survey of Earth.

These alternatives should buoy Denis Plunkett's continued belief in extraterrestrial interlopers. "I am just as enthusiastic about flying saucers as I always was," he told the *Times,* "but the problem is that we are in the middle of a long, long trough." Assuming "trough" means "lull," my calculations indicate that he shouldn't give up so easily. The bureau started in 1953, so being in the middle of the trough means that UFO sightings should be peaking no later than 2049. If by "trough," however, Denis means "feedbox," we should climb out immediately. Especially if there are any stray copies of that alien best-seller *To Serve Man* lying around. SA

ILLUSTRATION BY MATT COLLINS; PHOTOGRAPH BY FRANK VERONSKY

Q: How can sea mammals drink saltwater?

—C. Chen, Silver Spring, Md.

Marine biologist Robert Kenney of the University of Rhode Island offers the following explanation:

Although some marine mammals are known to drink seawater at least on occasion, it is not well established that they routinely do so. They have other options: sea-dwelling mammals can get water through their food, and they can produce it internally from the metabolic breakdown of food.

The salt content of the blood and other bodily fluids of marine mammals is not very different from that of terrestrial mammals or any other vertebrates: it is about one third as salty as seawater. Because a vertebrate that drinks seawater is imbibing something three times saltier than its blood, it must get rid of the excess salt by producing very salty urine. In the seal and sea lion species, for which measurements exist, the animals' urine contains up to two and a half times more salt than seawater does.

A marine mammal can minimize its salt and water balance troubles by following the same advice my doctor gave me to keep my blood pressure down: avoid salty food. Species that subsist on plants or invertebrates (such as crustaceans and mollusks) consume food with about the same salt content as seawater. These species thus face the same salt removal difficulty as they would if they drank seawater directly. In contrast, marine mammals that feed on fish consume food with a salt content similar to that of their own blood, thereby avoiding the problem. Indeed, a study of California sea lions showed that on a diet of fish these animals can live without drinking freshwater at all.

Some seals and sea lions apparently do drink seawater at least occasionally, as do common dolphins and sea otters, but the practice is very rare in other species. When given the choice, manatees and some pinnipeds will drink freshwater. (People who live on brackish waterways in Florida sometimes leave a garden hose flowing into the water to see the manatees come to drink.) Likewise, some seals will eat snow to get freshwater. For most whales and dolphins, however, we simply do not know how they get their water, because it is difficult to observe these animals. SA

For the complete text of this answer and many others, visit Ask the Experts (www.sciam.com/askexpert).

PATRICK HARDIN

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