THE HIDDEN BIOSPHERE: Is There Life Beneath the Ocean Floor?

SCIENTIFIC AMERICAN

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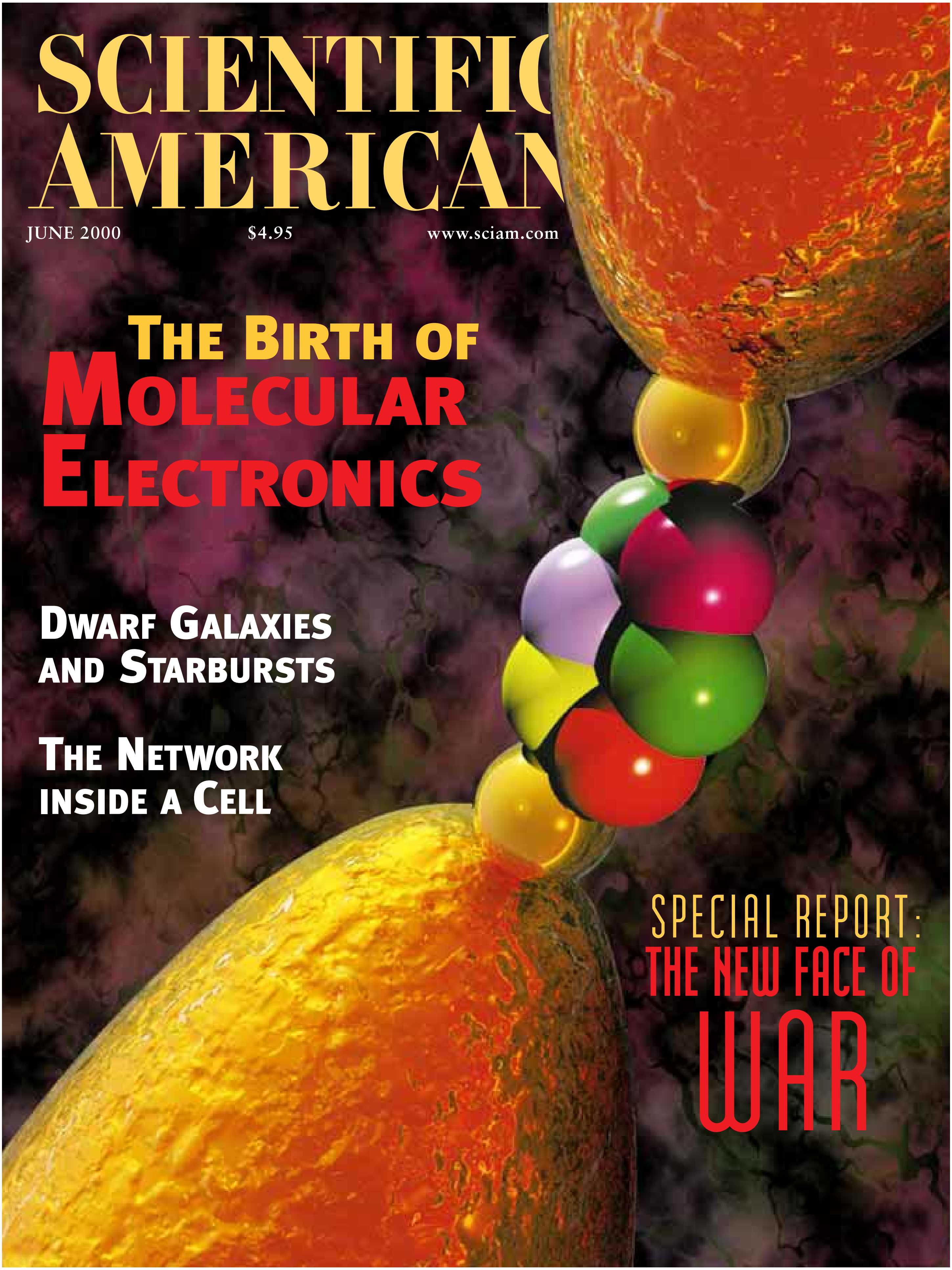

THE BIRTH OF MOLECULAR ELECTRONICS

DWARF GALAXIES AND STARBURSTS

THE NETWORK INSIDE A CELL

SPECIAL REPORT: THE NEW FACE OF WAR

SCIENTIFIC AMERICAN
June 2000 Volume 282 www.sciam.com Number 6

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EXPEDITIONS

Looking for Life Below the Bottom

Sarah Simpson, staff writer

Photographs by Paul Souders

Two researchers seek to prove that the largest repositories of life are *underneath* the oceans, inside the fractured rock of the crust.

About the Cover

An electrically conductive molecule stretches between two gold terminals. Image by Mark A. Reed.

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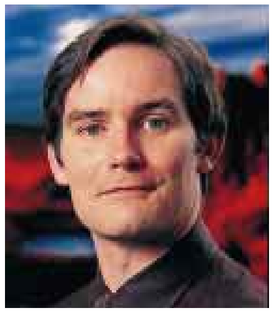
EDITOR_JOHN RENNIE

Nanotech Reality

For its fans, the umbrella of "nanotechnology" seems to cover any and all means of making molecules and atoms do what we want. Critics (and I've been one) argue that the field's definition is too vague and all-purpose to be useful, making it essentially impossible to argue whether nanotechnologists' predictions of, say, microscopic robots rearranging atoms on command are anything more than moonshine. Still, nanotech bulls and bears alike agree that the science of the extremely small progresses rapidly.

Many traditional chemists, molecular biologists, materials scientists and others have found that labeling their projects as nanotech suddenly makes them eligible for new sources of funding. Some privately express misgivings about being lumped in with the more wild-eyed visionaries, but if nanotech can claim anybody interested in the molecular or atomic scale of matter as one of its own, why shouldn't they help themselves to nanotech money and do good research with it?



ERICA LANSNER

Starting on page 86, Mark Reed and James Tour herald the possibility of molecular electronics—the use of individual molecules as transistors, wires and other circuit components. Part of their article's virtue is that it does not oversell the technology. Reed and Tour emphasize that limited experimental demonstrations of molecular electronics do not prove that scaling up for practical application will be easy or possible or that molecular electronics will necessarily be competitive with improvements in microelectronics. It is encouraging to see that Reed, Tour and others continue to advance their field so effectively while retaining a scientifically appropriate skepticism about it.

Which nanodevelopments are real and which are flea circuses?

Similarly, Technology & Business this month [see page 40] looks at how carbon nanotubes (a.k.a. "buckytubes") are finding a place in industry. They continue to have rich potential, but so far, at least for true buckytubes, the hype outruns the reality.

Under whatever label, all these technologies evolve and improve, to ends of as yet undetermined consequence. Scientific American and the experts who write for it will continue to watch and alert readers about which nanodevelopments offer genuine opportunities and which are still flea circuses.

No small achievement here: *Scientific American*'s longtime columnists Philip and Phylis Morrison have jointly dedicated more of their lives to the advancement of science and the public's understanding of it than anyone we know. Their decades of book review essays for this magazine, countless articles for others, and the classic volume *The Powers of Ten* have endeared them to more than one generation of readers, and their frequent lectures and appearances on television and radio have been inspirational. In recognition of the Morrisons' accomplishments, the National Science Board last month presented them with its Public Service Award. Previous recipients include Jane Goodall, Stephen Jay Gould and the public television series *NOVA* and *Bill Nye the Science Guy.* As always, Phil and Phylis, you have our sincere and somewhat awed appreciation.

John Rennie

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Cities for H-bombs,
Antibiotics for Industry

JUNE 1950

HYDROGEN BOMB: CIVIL DEFENSE—"The cities of the U.S., with their teeming masses of people and exposed industrial plants, afford targets of great attractiveness and high vulnerability to this type of weapon. It is obvious that if our largest cities could be dispersed into smaller communities, our nation would assume a much less vulnerable posture. One can raise the immediate objection of the astronomical costs involved. But planners today must take a long-range view of dispersion. Cities may be built in linear form extending for miles on end in a continuous thin 'strip city' pattern."

INDUSTRIAL ANTIBIOTICS—"The golden antibiotic aureomycin is more effective than vitamins in accelerating the growth of animals—by as much as 50 per cent in chicks, pigs and turkeys. Tests have showed that only .0004 of an ounce of aureomycin in a pound of feed increased the average rate of an animal's growth by about 10 to 15 per cent It has been suggested that aureomycin may aid growth by attacking detrimental microorganisms in the intestinal tract."

CONSPIRACY OF THE CREDULOUS—"Review: 'Worlds in Collision,' by Immanuel Velikovsky. The Macmillan Company ($4.50). Scientists consider Velikovsky's laborious theory that 3,500 years ago a great comet temporarily stopped the earth in its rotation to be one of the most astonishing hoaxes ever perpetrated on credulous man. Scientists of the social variety might even find it a study of mass psychology as interesting as the famous Orson Welles 'men from Mars' broadcast. The author seems unperturbed by such opinions."

JUNE 1900

WHAT TO BROADCAST?—"Mr. Richard Kerr has been exhibiting to the Royal Society in London his latest Hertzian wave [radio waves] system. This is a clock, the movements of which are controlled from a distance by means of wireless telegraphy. The inventor proposes to be able simultaneously to adjust all the clocks in London by means of this single timepiece. Every clock equipped with a receiver could be influenced, and the hands moved to any desired part of the dial."

VIETNAM AND FISH—"In Annam [central Vietnam] the number of persons who live mainly upon fish is estimated at five million. The region most abounding in fish is that of the southern provinces, Binh-Thuan and Khanh-Hoa, and that of Thanh-Hoa in the north. The latter district supplies fish to the Tonkin markets and part of China. The two former provinces, owing to the numerous bays where fishing may be carried on in all seasons, supply the salting establishments which furnish their products to Singapore and the extreme Orient."

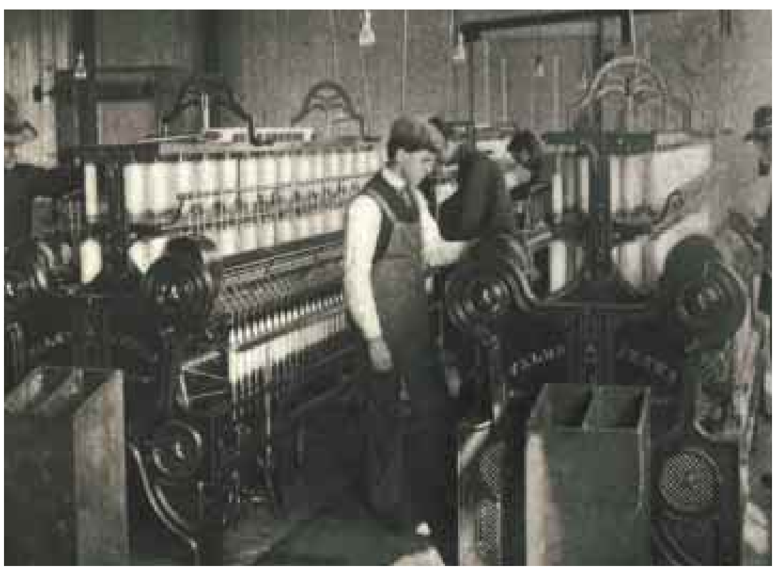
COTTON MILL SCHOOLS—"Manufacturers in the South are recognizing that the system of training workmen in the mill is ineffective, for the textile mill is an establishment whose chief purpose is production and not instruction. The first cotton trade school in the South is affiliated with the Georgia School of Technology at Atlanta; Clemson College, S.C., has also recently opened a textile department. The curriculums of these schools are as broad as their selection of machinery. Our illustration shows one of the young men learning on a ring-spinning frame."

TRANSMITTING POWER—"At the Paris Exposition all of the large engines are employed in driving dynamos, says *The Engineer,* and these supply power where it is wanted through cables. The 'mill engine' is not in evidence and may be ceasing to exist on the Continent. There is not a main driving belt nor a driving rope at work in the Exposition. This is evidence of the favor with which electrical transmission is regarded on the Continent."

JUNE 1850

THIS BUBBLE WORLD—"One great and growing sin of a national character is an inordinate desire to get rich and rich in a hurry. As wealth is the only aristocracy in America, every man seems bent on attaining to that important distinction. The 'haste to get rich' fosters a speculative spirit, and men rush hap-hazard into schemes for the sudden acquisition of wealth. Bubbles are blown, consequently, all around us. The man who amasses wealth thus suddenly rarely retains it, while his momentary success lures thousands to the same delusive pursuits. What can be more fatal to society than such practices?"

Scientific American



COTTON: a new trade school in the South, 1900

FROM SCIENTIFIC AMERICAN

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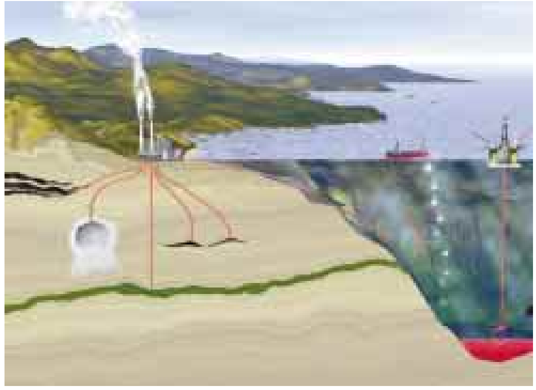

DAVID FIERSTEIN

CARBON DIOXIDE could be injected underground or deep in the ocean for long-term storage.

TREE OF LIFE

In "Uprooting the Tree of Life," W. Ford Doolittle suggests that all life-forms have emerged from the "common ancestral community of primitive cells." This, however, does not exclude the possibility that this community itself evolved from a common ancestor. This is a lot more probable than the independent appearance of several distinct life-forms at about the same time. Also, the article failed to mention another evolutionary mechanism of lateral gene transfer: transfer by viruses. Some viruses have a broad base of host species, so it is quite possible that lateral gene transfer has been taking place throughout evolution.

DIMITRI CHERNYAK
University of California, Berkeley

SEQUESTERING CO_2

In "Capturing Greenhouse Gases," Howard Herzog, Baldur Eliasson and Olav Kaarstad suggest that carbon dioxide can be captured from a stationary source, such as an electric power plant, and injected into the ocean or underground. They acknowledge that this may be costly and may pose a potential threat to the environment, but there is a more obvious problem. Energy would be required to separate the CO_2 from the waste stream, pump it underground or into the ocean, and regenerate the separation solvent. Unless a renewable source such as solar energy were employed, the amount of CO_2 generated by the energy needed to support these processes would offset the amount being sequestered. It would make more sense to focus on improving dependable greenhouse-gas reduction strategies, such as the use of renewable energy, low-carbon fuels and energy-efficient technologies.

BRUCE P. SMITH
Atco, N.J.

Herzog, Eliasson and Kaarstad reply:

The energy used to capture and sequester CO_2 comes from the fossil fuel itself, not a supplemental energy source. Thus, the net effect is a lowering of power-plant efficiency, not the release of CO_2. Researchers hope to reduce this "energy penalty," thereby curbing the cost of this approach. We would like to emphasize that CO_2 capture and sequestration is a complement to improved energy efficiency and nonfossil energy sources, not a substitute.

STANDS ON EVOLUTION

Thank you for "A Total Eclipse of Reason" [Commentary, October 1999] and "Fan Mail from the Fringe" [From the Editors, February], by John Rennie. Those of us teaching science at the high school level need the encouragement that these editorials provide as much as the Kansas authorities need discouragement for their actions.

Science teachers who teach evolution as a fact, even in a state like California, which at least officially encourages the teaching of evolution, still face subtle but strong pressures to water down the evolution curriculum. For new and untenured teachers especially, the sad tendency is to give short shrift to evolution or to teach it as a controversial idea. That's why such strong and uncompromising stands on this issue by a prestigious magazine are so important.

JAMES DANN
via e-mail

LOST TO GRAVITY?

With regard to "The Nonnegligible Lightness of Gravity," by Graham P. Collins [News and Analysis], if the earth "loses" 5×10^{-10} of its mass to gravitational binding energy, what is the fraction lost for a neutron star or a black hole?

JAMES G. STEWART
Dallas, Tex.

Collins replies:

For a neutron star of 1.4 solar-masses with a 10-kilometer radius, a naive Newtonian estimate predicts that the gravitational self-energy reduces the mass by about an eighth. A subtle point, however, is that no

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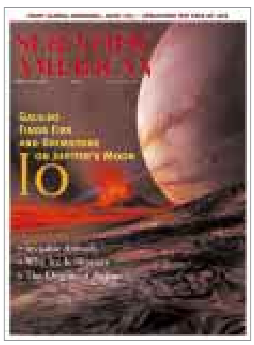


READERS OF THE FEBRUARY ISSUE flooded our mailbox with questions and comments on topics ranging from creationism to atmospheric carbon dioxide reduction. "A Breakthrough in Climate Change Policy?" by David W. Keith and Edward A. Parson [which accompanied the article "Capturing Greenhouse Gases"], for example, prompted several readers to challenge the authors' view of nuclear energy. Thomas Newton of the M.I.T. Nuclear Reactor Laboratory writes, "Keith and Parson neglect nuclear energy as a viable option in carbon reduction. They assert that nuclear energy plays only a 'minor role' as far as energy technologies are concerned, but it produces about 20 percent of the electricity in the U.S. and higher percentages in many other countries. In fact," Newton continues, "nuclear energy is the largest source of carbon-free energy production in the world, with the development of newer and safer plants in progress. The 'unfortunate history' of nuclear waste disposal that the authors refer to is entirely due to weapons production, not energy production." Keith and Parson offer the following response: "We agree that nuclear energy could be a substantial contributor to a low-carbon future. But with present plants aging and no new orders since 1978, its contribution to U.S. energy will continue to decline without major efforts to revive the industry and restore public trust. In the U.S. and worldwide, such revival will require fundamental changes in reactor design, management and public oversight." Additional responses to articles in the February issue are featured above.

mass-energy is actually "lost" to gravity. The books still balance, but with some gravitational entries in the ledger. Imagine that we drop iron asteroids on the earth until a neutron star forms. Each asteroid adds its rest mass and the kinetic energy it acquires from falling to the total. The gravitational self-energy also grows (becomes more negative). At the end the total mass-energy is still that of the earth plus all the asteroids. But if you add up the individual particle masses and all their energies (such as heat), to get the correct total you must subtract the gravitational self-energy. Gravitational energies become even more important for black holes, and the bookkeeping becomes even more arcane.

LEAD WEIGHT

Have you people lost your decimal point? Several decimal points perhaps? In David Pescovitz's "Please Dispose of Properly" [News and Analysis], the statement by Bob Knowles of the company Technology Recycling claiming eight pounds of lead in a computer monitor and three to five pounds of lead in a CPU is patently absurd. Even ounces would be an overstatement.

LLOYD HANSEN
via e-mail

Knowles replies:

Estimates of the amount of lead in computer systems vary widely because lead content varies depending on the age and make of the system. In addition, many people fail to consider all the areas in a computer system that contain lead. These areas include the monitor glass (which is ophthalmology-grade glass and is 30 to 35 percent lead); motherboards; circuit boards (including the one in the keyboard); and boards in disk drives, floppy drives and CD-ROM drives. According to the Northeast Recycling Council in Brattleboro, Vt., "on average, each monitor contains six pounds of lead," which is used in part to reduce the amount of electromagnetic radiation emitted. From this estimate, Technology Recycling calculates that some 41.4 million pounds of lead are discarded annually.

Even if one chooses a more conservative estimate of how much lead is in a computer system on average, the bottom line is that we are still facing a tremendous environmental problem.

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

ENVIRONMENT_GROUNDWATER CONTAMINATION

Toxins on the Firing Range

Over military protests, the EPA orders cleanups of unexploded ordnance

CAPE COD—In 1997 U.S. Army veteran Paul Zanis led military and Environmental Protection Agency officials to a buried stash of 1,100 mortar rounds, some live, located several hundred yards from a housing development. Zanis—an airplane mechanic who dresses in guerrilla garb and clandestinely roams the 22,000-acre Massachusetts Military Reservation on Cape Cod on his dirt bike scouting for pollution violations—also provided interesting photographs. They showed decaying artillery shells, flares, grenades and rockets—broken apart, lying on the ground, leaking toxic propellants and explosives such as RDX and TNT.

As a result of these findings and other data, this past January the EPA issued what its press release called a "unilateral" order, requiring the military to locate and remove unexploded ordnance (UXO) from the site's extensive training grounds. In the release, then EPA New England head John P. DeVillars said: "We need a comprehensive and expeditious cleanup of the extensive environmental damage caused by training activities." An estimated 10 percent of ordnance fired in battle and in training exercises does not explode on impact. Of prime concern is the Cape's only supply of drinking water, a vulnerable aquifer that is no more than 30 feet down in some places. Traces of pollutants have already been found in the ultrasandy soil and in the aquifer itself.

GREEN GUERRILLA: **Activist Paul Zanis searches for and collects unexploded munitions, which present a possible environmental hazard.**

JASON GROW *SABA*

The EPA order sets several important precedents. For the first time, the military has been directed to clean up UXO for environmental reasons, although it has frequently done so for safety. As authority for its decision, the EPA invoked the emergency provisions of the Safe Drinking Water Act, another first. Further, the agency issued the order preventively—on the basis of potential, future pollution of water supplies (the chemicals in UXO are suspected carcinogens). Although EPA officials believe that UXO leak and cause pollution, the charge has yet to be proved to the military's satisfaction.

Environmental advocates hailed the order as likely to have widespread national and even international ramifications. "It's been very difficult historically for regulatory agencies to tell the military [officials] that what they're training with or testing is bad for the environment," remarks Lenny Siegel, who is the head of the San Francisco–based Center for Public Environmental Oversight. "They don't want anybody to interfere with their mission."

Outraged at the order, military officials in Massachusetts initially argued that the EPA had overstepped its bounds. They also charged that digging up UXO that had penetrated the soil would be akin to strip-mining thousands of acres. "You don't want a 15,000-acre sandbox out there," says Kent Gonser, an environmental engineer working on UXO remediation. Moreover, the order affects "readiness of troops in training," because cleanup dollars would come from "beans and bullets" funds used for training, notes Lt. Col. Joseph L. Knott, who is in charge of National Guard training at the base. Finally, sweeping out the UXO now is premature, Knott claims, because "we lack scientific data. We just don't know what UXO does."

Knott is referring to the disagreement over whether the ordnance corrode over time, eventually leaking the chemicals. Until that is known, officials say, a cost-benefit analysis of the expensive and extensive work cannot be done. This summer military researchers will perform what has come to be called an "archaeological dig" at the Massachusetts base. Small sections of the base impact area will be excavated to a depth of 10 feet. All recovered ordnance, including fragments, will be documented. Chemicals present in the soil and water will be analyzed.

This battle is only the latest in the conflict over UXO. Nationally, environmentalists have been active at Buckley Field in Colorado, Camp Bonneville in Washington State, Fort Ord in California and Camp Greyling in Michigan. Internationally, University of Georgia marine ecologist James Porter recently discovered numerous live bombs and artillery shells lying on the delicate reefs surrounding the Puerto Rican target island of Vieques. Porter wants the UXO removed immediately. "They do leak," he says. "They constitute both a long-term and a short-term hazard to the coral reef." And at the U.S. Air Force's former Clark Air Base in the Philippines, UXO are creating some international diplomacy problems: children have shown up in Manila hospitals with leukemia that parents say is caused by weapons pollution. Privately, some military officials worry that the Massachusetts order could force action at these other sites, although publicly they insist that Cape Cod's situation is unique and will not, therefore, apply elsewhere.

The EPA insists that UXO pose a serious environmental threat and that it has not received adequate answers. In a 1999 letter to Deputy Under Secretary of Defense Sherri W. Goodman, EPA official Timothy Fields, Jr., wrote that the "EPA has become increasingly concerned with the UXO and hazardous chemical contamination situations at military ranges nationwide. For many reasons, it appears that closed, transferred and transferring military ranges are not being adequately addressed in a manner consistent with accepted environmental or explosive standards and practices. Judging by the increasing number of sites with UXO or UXO-related issues, we are now at a juncture where these issues need both your and my immediate attention."

ORDNANCE RETRIEVED by Zanis (some of which were only dumped on the Cape Cod grounds) include a World War I 155-millimeter artillery projectile (*center*), in addition to machine-gun blanks, flares, aircraft chaff and mortar rockets.

Fields says that of the thousands of military properties around the nation containing UXO, probably about 200 have "large range areas with UXO-caused contamination that is threatening some aspect of the environment." An estimated 5,000 to 8,000 ranges contain UXO. This number may increase after further Department of Defense research, necessary because "many former range area locations were not documented and are no longer known," according to a 1998 EPA memorandum. Few records on UXO disposal exist, in part because the act of burying munitions was often furtive. "It was just an easy way to get rid of them," Zanis says. "If guys had 100 artillery rounds to fire, they might only fire 80 of them. It's difficult to resubmit the rounds to the ammo supply point, so they would just bury them. Sometimes they would just drive a truck to the landfill and just dump them."

Military officials deny allegations that UXO cause environmental damage and resultant human health problems such as cancer. In a 1997 memorandum, Col. W. Richard Wright wrote that "the potential for contamination occurring from munitions breaking up on impact is virtually zero.... There is no archival or anecdotal evidence that UXO 'break up' on impact." Privately, some military personnel allege that photographs of broken and leaking UXO, like those presented by Zanis, have been staged. Moreover, they say, agencies ordering UXO cleanups must also consider the danger inherent in the job. Last summer two contractors removing UXO for safety reasons at Fort Drum, N.Y., received serious fragment wounds from an unexpected detonation.

At the heart of the controversy is the lack of hard data on both sides. Even Siegel calls the extant science "primitive." Although the military apparently admits today that at least some UXO do leak pollutants, no one knows how many do so, why they leak or what happens to the chemicals once the shell has corroded. The military's Jeff Marqusee, who is responsible for managing the necessary research, says the UXO question has only recently appeared on national radar screens. Finding the answers will take time, he states, adding that the process of organizing research studies is already under way. Comments air force environmental policymaker Tad McCall: "We [at the DOD] have the key to unlock our own cell, and that's in science." But, McCall cautions, action should be limited until the research is in.

Despite initial claims of $320 million, the cost of cleaning up the Cape Cod UXO is really unknown, because no one knows what's out there. But it's bound to be expensive. On the Hawaiian island of Kaho'olawe, where the military is cleaning up an area of similar size, the total project is expected to cost several hundred million dollars. And at the Massachusetts site, with its 20-year history of poor community relations, a strong public participation effort—also expensive—must be made, notes air force environmental troubleshooter Col. John Selstrom, currently an aide to the DOD's Goodman. "All the stakeholders' needs must be met" if there is to be any resolution, Selstrom observes. He adds that the military deserves credit for learning over the past decade how to be a better neighbor, pointing out that "green" bullets—in which less hazardous tungsten is substituted for lead—were first used in training exercises at the contentious Massachusetts site.

Despite the military's stance, DOD officials say they will comply with the EPA's unilateral order, and since then both sides have backpedaled a bit on their more dramatic claims. The information coming into the EPA as a result of the order, remarks the agency's New England counsel, William Walsh-Rogalski, "is going to provide more really useful information than anyone's found before. Everything we're asking [the military] to do is reasonable. It just hasn't been done before." —*Wendy Williams*

WENDY WILLIAMS, a freelance writer based in Mashpee, Mass., described the controversy surrounding the use of the insecticide chlorfenapyr on farms in the October 1999 issue.

JASON GROW SABA

A Plum of an Island

Sensationalism dogs an animal laboratory upgrade

PLUM ISLAND, N.Y.—"We still get asked about the Nazi scientists," says Sandy Miller Hays, the slightest trace of weariness creeping into her voice. We're sitting on the ferry that will bring us back from Plum Island, where the U.S. Department of Agriculture (USDA) operates one of the world's top laboratories for the study of infectious animal diseases.

Foot-and-mouth disease and African swine fever would not seem to be the stuff of wild urban legend anymore. Nevertheless, the rich mythology that has sprung up around the 840-acre island makes it a must-see stop on the conspiracy theorist's world tour. Hays, information director for the department's Agricultural Research Service, which oversees the laboratory, patiently describes several of the choice tales she's been asked about over the years. The gist of the "Nazi scientists" story is that after the war the army (which did actually use Plum Island as a base to hunt U-boats) brought German scientists to the island to develop biological-warfare agents. Lyme disease, first identified in nearby Connecticut, was caused by one of their escaped microbes, according to the tale. Other stories feature three-headed mutant chickens, space aliens in storage and a secret submarine laboratory.

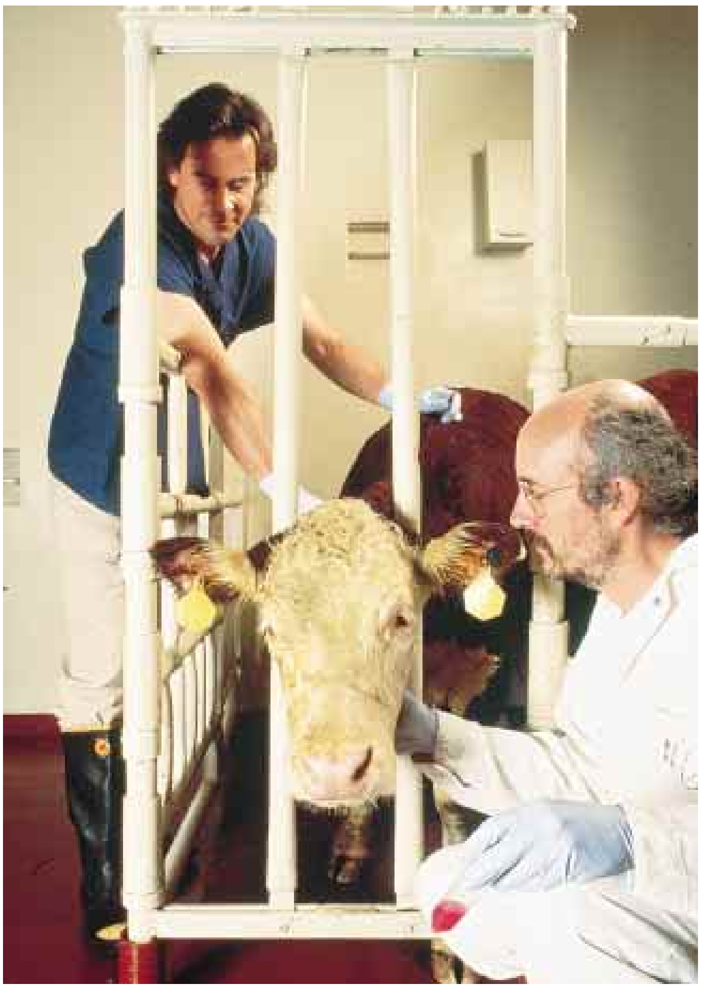
The threads that went into the fanciful fictional tapestry that shrouds Plum Island are fairly obvious. The USDA did not let any reporters onto the island between 1978 and 1992. Then, novelist Nelson DeMille stoked the fire with his 1997 thriller *Plum Island,* about a detective investigating the murder of two biologists amid suggestions that they stole a secret vaccine-in-progress. It also didn't help that the island is just 1.5 miles off the North Fork of Long Island, the standard-bearer for suburban luridness.

Unfortunately for the USDA (and Hays in particular), the lab's reputation has complicated its most recent quest: selling nearby residents on its proposal to upgrade the lab from its current rating of biosafety level 3 to level 4, the most secure. The USDA wants the upgrade so that it can study potentially fatal diseases that can jump from animals to people. No animal-disease lab in the U.S. has a level-4 rating, but there are such labs in Geelong, Australia, and Lyons, France, as well as a small one in Winnipeg, Canada. The U.S. does maintain several level-4 labs for human diseases—including one in downtown Atlanta at the Centers for Disease Control and Prevention.

Before beginning a tour of the laboratories and animal-holding pens, the assembled members of the press (there are four of us) strip off our clothes. Conveniently, none of us has any hidden body piercings, which might collect microbes, so we are free to put on coverall garments and enter biocontainment. (Jewelry in a pierced part would have to be left behind.) Essentially all the facilities are located in a single large building known, with comic arbitrariness, as Building 101.

The point of the tour is to impress on us how serious the laboratory is about safety and security. An official describes the powerful filtering and ventilation system that directs airflow so as to contain any stray microbes within certain rooms. We are shown the airtight and watertight steel boxes within which infectious materials are delivered. A technician with gloves and safety glasses demonstrates that the boxes are opened under a hood. Samples are stored in sealed vials in cardboard boxes in freezers. All contaminated trash is treated in an autoclave before being incinerated. Even the sewage is decontaminated before being released. Such prosaic stuff is a long way from mutant chickens.

At last we descend into



ANIMAL-DISEASE TESTING, such as inoculating a steer with an experimental vaccine, takes place on Plum Island (*inset*), just off Long Island's Orient Point.

AGRICULTURAL RESEARCH SERVICE, USDA

the mazelike bowels of the building for a tour of the animal-holding pens. We see pigs, a cow, guinea pigs and some rabbits. Six young pigs in a fluorescent-lit painted-cinder-block room are destined for a safety test, explains Lee Ann Thomas, the lab's acting director. To ensure that an animal-derived product being tested is free of any exotic viruses, the pigs will be inoculated with the product—possibly cell cultures or hormones. Later the pigs' blood will be checked for antibodies. Products singled out for testing come from animals known to be at risk for certain infectious diseases, or they come from countries where those diseases are endemic.

Before we can leave the biocontainment area, we must remove our borrowed coveralls and shower thoroughly. Our eyeglasses—and the waterproof video camera with which the two TV journalists have been gathering footage—are dunked in an acetic acid solution for a few minutes before being released.

"We don't know what diseases are coming, but we know they're coming," Hays says in making the case for the level-4 upgrade. As examples, she cites Nipah and Hendra, recently discovered viruses borne by swine and horses, respectively. Both viruses are known to have jumped fatally to people, primarily farm and slaughterhouse workers. A Nipah outbreak killed about 100 people in Malaysia in 1999, and Hendra caused two deaths in Australia in 1994. Neither virus made it to the U.S., but if one had, Hays asserts, no lab in the U.S. would have been equipped to study it. (The infamous West Nile virus, which is deadly to birds, was briefly studied at Plum Island last year. Because West Nile is seldom fatal to people with robust immune systems, it can be studied in a level-3 laboratory.)

More intriguing (though still not in the three-headed chicken category) is the question of whether the lab will do work on vaccines to counteract germ warfare or bioterrorism agents—specifically, ones developed to kill both livestock and people. "There were a number of reports of agents being weaponized" in Russia, Thomas notes. But she denies that the proposed upgrade is tied to a specific agenda to develop germ-warfare countermeasures at Plum Island, as some reports have suggested. "Whether it's an intentional introduction [of a virus] or an accidental introduction," she says, "the need to protect the animals is going to be the same."

—Glenn Zorpette

Soothing the Inflamed Brain

Anti-inflammatories may be the first drugs to halt the progression of Alzheimer's

VANCOUVER—Edith G. and Patrick L. McGeer are in their 70s, and after 15 years of research and 670 autopsied brains, they know only too well the odds of developing Alzheimer's. About 10 percent of those older than 65—and nearly half of those older than 85—have the disease. But they also know exactly what they'll do if, or even before, the disease strikes. They'll take the kind of drugs millions rely on to relieve their headaches and joint pain—drugs in the same class as ibuprofen and aspirin. The McGeers, husband-and-wife neuroscientists at the University of British Columbia, are betting on nonsteroidal anti-inflammatories as the first way to slow Alzheimer's.

Alzheimer's researchers have had anti-inflammatory agents on their radar screen since at least the early 1990s, when the McGeers and their colleague Joseph Rogers of Sun Health Research Institute in Sun City, Ariz., noticed a startlingly low occurrence of Alzheimer's in arthritics. More than 20 follow-up studies made the link to anti-inflammatories. No one knows exactly why that link exists—the ultimate cause of Alzheimer's itself is still foggy—but the McGeers believe it is related to the growing but still unproved theory that the disease can best be described as the brain's own immune system turning on it.

The characteristic plaques and tangles found in the brains of Alzheimer's sufferers are filled with compounds, especially the protein beta-amyloid, that can kick-start the brain's innate immune system. Ancient and primitive, isolated from the rest of the body, the brain's immune system can be "ferociously active," Edith McGeer says. Its primary workers are microglial cells, the brain's equivalent of macrophages, which engulf and degrade intruding debris. In Alzheimer's brains, the plaques and tangles are marked for microglial destruction with the proper protein tags, but then something goes haywire. The microglial cells begin producing toxins that kill off good cells along with the bad. That further provokes the brain's inflammatory response, which kills more neuronal cells, setting up a vicious cycle. Once the damage has been done, nothing can reverse it. "What the brain is doing is mistaking friend for foe," Patrick McGeer explains.

The process can be described as inflammatory even though the brain doesn't swell or become painful like an inflamed joint. If the brain had pain receptors, Alzheimer's would undoubtedly hurt—and be detected much earlier. As it is, plaques and tangles may start forming 20 or 30 years before any symptoms begin to show.

HUSBAND-AND-WIFE research team of Patrick and Edith McGeer has high hopes for dapsone, a leprosy drug.

TED GRANT *Zuma Press*

The only drugs now approved for treatment of Alzheimer's in Canada and the U.S.—tacrine (sold under the name Cognex) and donepezil (sold as Aricept)—temporarily boost memory, often by inhibiting cholinesterase, an enzyme that breaks down neurotransmitters. They don't address the cycle of neuronal cell destruction—but anti-inflammatories might.

"If you can decrease the amount of inflammation, it should decrease the amount of damage," reasons Bill Thies of the Alzheimer's Association, based in Chicago. And that in turn should slow the onset of dementia. "If you can slow the progression . . . past the point of death," Thies notes, "then you've effectively ended the disease."

The McGeers have concentrated their work on dapsone, an anti-inflammatory used for decades to treat leprosy. In a 1992 study in Japan of 3,782 leprosy patients, the prevalence of dementia was 2.9 percent in those continuously treated with dapsone or a closely related drug (promine), compared with 6.25 percent in the untreated group. When the treated patients were taken off the drug, the incidence of Alzheimer's shot up. In the second half of this year, through the Vancouver-based company Immune Network Research, dapsone is going straight to a phase II clinical trial for use with Alzheimer's. (It needs no phase I approval, which determines drug safety, because it is already approved for leprosy.)

Dapsone joins a range of other anti-inflammatories that are under trial or investigation for Alzheimer's treatment. Merck and Monsanto have their own, so-called COX-2 inhibitors named Vioxx (rofecoxib) and Celebrex, which are in phase III trials this year; both are already sold to treat arthritis. And the National Institute on Aging launched a 14-month trial in February with rofecoxib and naproxen. The McGeers suspect the best solution will be a combination of drugs, and dapsone can be added to that list.

Both dapsone and the COX-2 inhibitors seem free of the major side effect that plagues many anti-inflammatories—mild gastrointestinal bleeding and stomach pains. But even anti-inflammatories that carry that small risk seem well worth it when compared with the devastation of Alzheimer's. Says Patrick McGeer: "I'll take brains ahead of guts." *—Nicola Jones*

NICOLA JONES is a freelance writer based in Vancouver, B.C.

AVIATION_FLIGHT CONTROL

Throttled

Manufacturers balk at steering and landing with engine thrust alone

It has become the stuff of piloting lore. In 1989 the rear engine exploded on United Airlines Flight 232 en route from Denver to Chicago, sending hot shrapnel through the fuselage and severing the main and backup hydraulic lines that kept the DC-10's flaps, ailerons and other control surfaces functioning. At 37,000 feet, with no controls at all, the crew flew the crippled airliner the only way they knew how: by manipulating the power settings of the two engines that remained. And it almost worked. Arduously lined up on a runway at the airport in Sioux City, Iowa, the DC-10 swerved at the last moment—before the crew could react—then tumbled out of control and exploded. One hundred twelve passengers and crew members died, but through luck and superb flying, 184 survived.

Though shocking, the incident was not unique. According to the National Aeronautics and Space Administration, in the two decades preceding the Sioux City crash approximately 1,100 fatalities were caused by loss of flight controls in aircraft. But Flight 232 did spur some NASA engineers to act. Soon after the tragedy the Dryden Flight Research Center in Edwards, Calif., began a program called Propulsion Controlled Aircraft (PCA), designed to see if pilots could safely control and land jet aircraft by engine power alone. Theoretically, it's simple: add power, and the aircraft climbs; reduce power, it descends; to turn, add power to one engine and reduce it in the other. In reality, though, manual propulsion control is a sticky situation: inputs to the engines must be small and precise, and thrust response in jet engines is slow.

For a computer, however, it's no sweat—especially on new "fly by wire" aircraft that rely on all-digital flight controls. Dryden engineers Frank W. (Bill) Burcham, Jr., and Glenn B. Gilyard (both now retired) found they could quickly and easily link bank-angle and flight-angle commands through the autopilot to computers that controlled the engines. This would allow a pilot to enter commands onto a control panel, and those commands would translate into commands to the engine. Flying a modified MD-11, test pilot and space shuttle astronaut Gordon Fullerton managed a series of four engine-only landings in August 1995. "We were stunned at how controllable it was," Fullerton says.

Although retrofitting older aircraft with PCA would be difficult and expensive, doing so on fly-by-wire systems is easy and economical, the Dryden team maintains. Yet neither major airline manufacturer plans to incorporate the technology. According to a statement by Airbus Industrie, "a total hydraulic failure is extraordinarily unlikely, simply because of the redundancy of the cockpit's electronic systems and the mechanical backup to those systems. So the propulsion-control system really doesn't have any immediate relevant application to our aircraft." Boeing concurs: "We are very familiar with how the 'Propulsion Controlled Aircraft' works," the company acknowledged in a statement, "but we believe the real value is in preventing deterioration of the normal control system."

The Dryden team says, however, that the reticence may go deeper than that. "It's all politics," Gilyard contends. "If anybody stops and says, 'We need [PCA],' it's sort of implying that the airplanes aren't safe." And admittedly, the odds that an airliner will lose all its controls and backup systems are slim. "The manufacturers felt they were better off spending the time training pilots on more likely problems" than total control failure, Burcham states. (PCA probably would not have made a difference in this past January's Alaskan Airlines Flight 261 crash, believed to have been caused by a worn jackscrew that controlled the horizontal stabilizer.)

To entice the manufacturers, and to further explore the limits of PCA, in 1998 the Dryden engineers tested two scaled-down propulsion-control systems, called PCA Lite and PCA Ultralite. Neither requires changes in an airliner's engine-control computer, and both need less pilot training. Still, no manufacturer is biting.

Meanwhile Dryden last year began tests on what it calls Intelligent Flight Controller (IFC), which, along with PCA protocol, incorporates adaptive neural networks in its software. With such networks, the IFC would compensate for loss of a control surface by changing the configuration of the remaining control surfaces and altering engine thrust, explains project participant Ken Lindsay.

Burcham says he's not too disappointed with the lukewarm reception PCA has received from the industry. "We did have 20 pilots, representing a number of airlines and manufacturers, fly the MD-11 system, and we hope they got the word out that it is possible to fly with throttles alone," he remarks, adding that Fullerton has also spoken about the technique to industry groups. "Not since Sioux City has an airplane had total hydraulic failure, so that's the good news," Burcham observes. "But it could happen any day." *—Phil Scott*

PHIL SCOTT specializes in aviation issues and is based in New York City.

NASA

LOOK MA, NO FLAPS: Testing in 1995 showed the ability of software to land an MD-11 on engine thrust alone.

MOLECULAR BIOLOGY_GENOMICS

SNPs of Disease

The U.K. plans a national genomic database to study late-onset sickness

If, as biochemist and Nobel laureate Paul Berg of Stanford University has said, all diseases have some genetic basis, then deciphering the human genome will be essential to longer, healthier lives. Efforts to do so are rocketing to the finish line—Celera Genomics announced in early April that although it had not yet put the code together, it had identified all the genetic pieces (their claim, however, is disputed by other scientists). But to transform genomic data into 21st-century medicine, researchers must correlate genes to specific conditions.

With that in mind, British researchers are preparing to enlist 500,000 physician-recommended adults who would each contribute a blood sample. Their DNA would go to a national database to be created by two powerful funders of U.K. medical research: the Medical Research Council (MRC) and the Wellcome Trust.

The blood samples will reveal polymorphisms—variations in the genome sequence. Although 99.9 percent of the sequence is identical in all humans, the remaining 0.1 percent includes some differences that are responsible for disease. These variations—called single nucleotide polymorphisms, or SNPs (pronounced "snips")—occur in only one nucleotide base out of every 1,000 of the three billion bases in the human genome. In April 1999 the SNP Consortium—a group of pharmaceutical companies, research institutes and the Wellcome Trust—was formed to map 300,000 SNPs.

The U.K. project would go beyond the SNP Consortium's by correlating genetic variations with diseases. Data would be recorded about participants' current health (the U.K.'s National Health Service has 50 years of records of the patients and their families) and the diseases they develop; lifestyle and environmental details would supplement the findings. Adults between the ages of 40 and 70 would be targeted.

Thomas W. Meade, a director at the MRC and chair of the database panel, characterizes the project's goals as understanding and addressing the genetic causes of late-onset disease, developing and targeting new treatments, and assessing an individual's risk so that preventive measures can be taken. The data should also give the British pharmaceutical industry a leg up.

Despite its substantial genetic research, the U.S. itself is unlikely to mount such a project. First, a central repository of medical records does not exist in the U.S.; second, Americans would be justifiably worried about how their genetic data would affect their insurance coverage. Although private genomic database efforts in other countries are under way—one run by deCODE in Iceland and another by Gemini Holdings in Newfoundland and Labrador, Canada—those studies focus on populations descended from a small founder group. Such an approach is better suited to finding relatively rare genetic disorders.

Several concerns about access and privacy naturally arise. The MRC maintains that all its information would be stored and analyzed in a form that would not allow individuals to be identified. But few details have been provided about how confidentiality would be assured. Meade says that pharmaceutical companies will have access to the information under carefully regulated conditions and with the patients' active, informed consent.

The U.K. may extend testing even further. In March a government committee recommended a national program for pregnant women. The proposed policy would go far beyond the current screening system to ensure that all pregnant women believed to be more susceptible to certain disorders would be offered testing. Although predicting health risks may be possible soon, healing from the genome still lies in the future. —*Arlene Judith Klotzko*

ARLENE JUDITH KLOTZKO, a bioethicist and lawyer based in New York City, is editor of the forthcoming anthology The Cloning Sourcebook *(Oxford University Press).*

COMPUTERS_PRIVACY

The Orwell Awards

In recognition of efforts to trample personal liberties on the electronic frontier

TORONTO—1984 was 16 years ago, but the culture of surveillance is still in full swing, say privacy advocates who gathered for the Orwell Awards 2000, presented at the 10th annual Conference on Computers, Freedom and Privacy. In a ceremony that opened to the rousing strains of *South Park*'s "Blame Canada," Simon Davies of Privacy International in Washington, D.C., presented the "honors" to those in the U.S. deemed by a panel of judges to have posed the worst threats to privacy in the past year.

Davies, dressed as the glossy-pated Dr. Evil from the Austin Powers films, started with the Worst Single Project category, whose laurels went to the Federal Aviation Administration's idea to deploy whole-body x-ray scanners in U.S. airports. A fictitious "Dr. Milton Exray," accepting the award on behalf of the FAA, extolled future developments, including ultrasound and DNA profiling to take pictures of potential terrorists even before they are born.

(Such fantasies of state intrusion may have been superfluous in the face of real government initiatives such as the U.K.'s

PRIVACY INTERNATIONAL

THE NOT SO COVETED Orwell trophy

proposed Regulation of Investigatory Powers statute, which would compel citizens to decrypt any file that a law-enforcement official believes to contain data needed for an investigation. Those who fail to do so and cannot prove they have lost, forgotten or destroyed the presumed key could face two years in jail.)

The Worst Corporate Offender title went to the advertising firm DoubleClick for its plan to link the Internet surfing habits of 50 million people to a database of names, addresses, telephone numbers and demographic information from a marketing company with which it merged. DoubleClick had previously made public statements that the information would always be kept anonymous. After public outcry and a barrage of lawsuits earlier this year, the company called off the linking project, saying that it would wait until the relevant law was clarified.

The competition in the category was tough, observed presenter Jason Catlett of the privacy-advocating firm Junkbusters. DoubleClick had to beat out both Naviant, a start-up that sells information from on-line product registration forms to direct marketers and others, and telecom giant USWest, which has been fighting to use its records of virtually every telephone call made in 14 states for marketing and additional commercial leverage.

Combined recognition for Worst Public Official and Most Intrusive Government Agency went to William Daley and the Department of Commerce, which he heads. Presenter Barry Steinhardt of the American Civil Liberties Union cited the department's long-standing battle to prevent the dissemination of information about cryptography (recently overruled in federal court) and to bar the export of cryptographic software (abandoned this spring by the Clinton administration). He also chided Daley's efforts to negotiate a regulatory agreement whereby companies in the U.S. will be able to process information collected in Europe, where it is protected by law. The European Union has thus far rejected this "safe harbor" accord.

To cap the department's efforts, Steinhardt noted, the Federal Trade Commission continues to oppose government action on Internet privacy, despite having issued reports detailing the failure of industry to regulate itself. (Elsewhere at the conference, FTC Commissioner Mozelle Thompson commented that the EU's one-size-fits-all policy of protections for all kinds of personal information was not suited to the U.S.)

Finally, the Lifetime Menace award went to Trans Union, which maintains credit histories for a purported 90 percent of U.S. adults. The company has made the information available on request to, among others, loan officers, private investigators and used-car sellers. Estimates of erroneous records range from 10 to 50 percent, depending on whether one counts all errors or only those that damage a credit rating. In addition to private lawsuits, the company has been fighting FTC oversight for more than eight years.

"Accepting the award will be Trans Union's vice president of legal affairs, Darth Vader," joked David Banisar of the Electronic Privacy Information Center, handing the Orwell boot-stomping-on-head statuette to a costumed proxy. Banisar noted that the company had beaten out a host of others—including the National Security Agency, whose global-monitoring system is considered by most privacy advocates to be second to none. *—Paul Wallich*

HEALTH_CHRONIC DISEASES

Asthma Worldwide

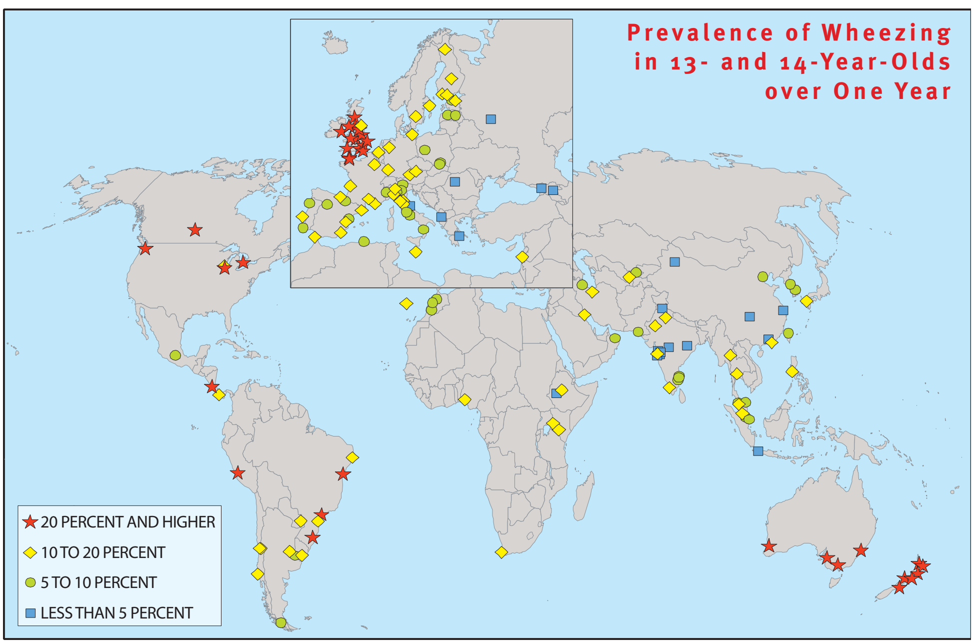
Asthma was rare in 1900, but now it has grown into an epidemic: more than 15 million are affected in the U.S. and up to 10 times that many around the world. Every year it kills 5,000 Americans, mostly older adults, and 180,000 annually worldwide, according to the World Health Organization. Why asthma rates have risen is not entirely understood, but clues come from studies showing that its prevalence tends to be highest in Western countries, particularly the English-speaking ones; it is virtually absent in parts of rural Africa. The map shows data on the prevalence of wheezing—a commonly used indicator of asthma—for 13- and 14-year-olds, taken from one of the largest epidemiological studies, the International Study of Asthma and Allergies in Childhood. Among this age group the pattern of wheezing is about the same as that in younger children and adults.

Although having an asthmatic parent—or, worse still, two asthmatic parents—increases a child's risk, there seems to be a consensus that differences such as those depicted on the map result not primarily from genetic factors but from environment and lifestyle. Precisely what elements are involved is not entirely clear. Among the candidates is the tendency of children to spend more time indoors than did those in earlier generations, thus increasing their exposure to household allergens, including dust mites, cats and cockroaches. According to one popular theory, the pulmonary immune systems of Western children, unlike those in developing countries, do not mature properly, because they are not conditioned to live with parasites, and so the children become more vulnerable to asthma and other allergic diseases such as hay fever and eczema.

Perhaps half of all asthma takes the allergic form, which is associated with a family history of the disease. In the nonallergic form, which is more likely to affect adults, there is no family history of allergy, and the initiating factor may be as simple as a common cold, which develops into paroxysms of wheezing and shortness of breath that may go on for days or months. In both types the tracheobronchial tree becomes hypersensitive, and the diameter of the airways shrinks. Acute episodes are typically followed by symptom-free periods. Although asthma is more prevalent among children—it is now the most common chronic childhood disease in the U.S.—twice as many adults have it. Perhaps one in 10 adults with asthma contract it through exposure to occupational agents such as reactive dyes.

In addition to household contaminants, asthma can be precipitated by exercise, cold air, emotional stress, viral infections, everyday chemical agents such as aspirin, and industrial air pollutants, including ozone and nitrogen dioxide. There is no evidence, however, that outdoor air pollution is an initiating cause of asthma. Inner-city poverty is a risk factor: asthma mortality, for example, is highest among Americans of Puerto Rican and African descent. Smoking exacerbates asthma, and maternal smoking during pregnancy increases the risk for the child. Obesity is also associated with asthma.

With such a variety of factors, it is no wonder that scientists don't fully understand the natural history of the disease. Even so, they have made remarkable progress, notably with drugs such as inhaled steroids. These and other new treatments, if used regularly by all asthmatics, could for the most part prevent deaths from the disease. *—Rodger Doyle (rdoyle2@aol.com)*



SOURCE: *"Worldwide Variations in the Prevalence of Asthma Symptoms: The International Study of Asthma and Allergies in Childhood (ISAAC)." M. I. Asher et al. in* European Respiratory Journal, *Vol. 12, pages 315–335; 1998. Data based on surveys of 463,801 children in 155 centers and 56 countries. Fieldwork conducted in 1991–95. Map reprinted with permission from the ISAAC Steering Committee on behalf of the ISAAC Phase One Study Group and with permission from the* European Respiratory Journal.

COMMUNICATIONS

The 300-Gigahertz Light Switch

Modern communications networks, such as fiber-optic cable-television lines, require devices called electro-optic modulators, which convert electrical signals into light pulses. To do so rapidly, most modulators, such as lithium niobate crystals, require about five volts—a relatively large amount that limits gain and introduces noise. Chemists and engineers from the University of Southern California and the University of Washington report in the April 7 *Science* that they have created a swift-working polymer modulator that requires only about 0.8 volt. The trick was to shape the dopants, called chromophores, in ways that kept them from aligning and so producing electrostatic charges that disrupted the electro-optical modulation. The bandwidth of the new modulator is 300 gigahertz—enough to handle all of a large company's telephone, television and computer traffic or to make possible flicker-free holographic image projectors, according to the investigators. *—Philip Yam*

ASTRONOMY

Long Tail of the Comet

Hyakutake in 1996

JEFF VANUGA *Corbis*

"Comets are like cats," famed comet discoverer David Levy has said. "They both have tails, and they both do exactly what they want to do." The unpredictability of these interplanetary vagabonds has been demonstrated yet again, this time by the Ulysses space probe. On May 1, 1996, the sun-monitoring spacecraft, circling the sun along a path at right angles to the plane of the earth's orbit, passed through a patch of plasma quite unlike any material flowing out from the sun. Exactly what had happened astronomers couldn't fathom, until a team led by Geraint H. Jones of Imperial College, London, realized that the patch lay on a line extrapolated from Comet Hyakutake, some 550 million kilometers away. That makes Hyakutake's tail of charged particles nearly four times as long as the distance between the earth and the sun and seven times as long as photographs had shown. Indeed, the tail may hold together even farther out, perhaps to the very edge of the solar system—contrary to expectations that tails rapidly disperse. The discovery, reported in the April 6 *Nature,* also opens up a new way of detecting comets and sampling their material. *—George Musser*

METEORITES

Yukon Gold

Thanks to a resourceful Canadian, scientists have obtained a 4.5-billion-year-old relic of the solar system's beginnings. On January 18 a 50-ton meteorite exploded over Canada's Yukon Territory. Soon afterward a resident of the sparsely populated area found some crumbly black rocks on the snow-covered ground. He placed them in plastic bags and kept them frozen until he could contact a geologist. They turned out to be fragments of carbonaceous chondrite, a type of meteorite that rarely reaches the earth's surface—the last one recovered was the 1969 Murchison meteorite. More important, never before has such a meteorite been examined in a pristine condition. Researchers hope to probe the rocks for organic compounds, which may hold clues to the origins of life. *—Mark Alpert*

SIDNEY HARRIS

MEDICINE

Yes, Sharks Get Cancer

Talk about a fish story: legend has it that sharks don't get cancer, making the creature's cartilage popular in the alternative health market as a cure for the disease. But John Harshbarger of George Washington University, a pathologist who studies tumors in animals, told the American Association for Cancer Research in April that sharks (and their close relatives, skates and rays) can and do develop cancer. Sales of shark-cartilage supplements, derived mainly from spiny dogfish and hammerheads, exceed $25 million a year; an estimated 100 million sharks are killed annually, putting some varieties on international endangered species lists. *—Sasha Nemecek*

JEFFREY L. ROTMAN *Peter Arnold, Inc.*

DATA POINTS

Cash Only

U.S. DEPARTMENT OF THE TREASURY

On May 24 the U.S. Treasury began issuing new $5 and $10 bills, which join the redesigned $20, $50 and $100 bills. They incorporate features that make counterfeiting more difficult.

1. **Watermark** Visible from both sides when held up to light source.
2. **Security Thread** Glows orange under ultraviolet light.
3. **Fine-Line Printing** Difficult to replicate.
4. **Microprinting** "TEN" is repeated in the numeral; "The United States of America" is repeated directly above Hamilton's name.
5. **Color-Shifting Ink** Green number appears black when viewed at an angle.

Counterfeit U.S. currency worldwide, 1999: **$180,872,588**
Amount seized prior to circulation: **$140,266,388**
Total U.S. currency in circulation: **$480 billion**

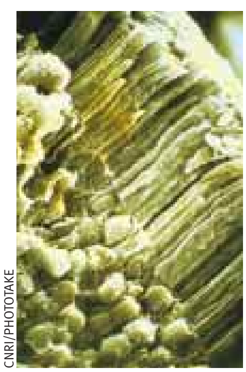
Cost to print a legal note: **4.2 cents**
Number of notes printed, 1998: **9.2 billion**

SOURCE: U.S. Department of the Treasury

NEURAL REGENERATION

An Eye for an Eye

Studying the mammalian retina, researchers have located stem cells—the progenitor cells that give rise to all the tissues in the body. The scientists, from the Canadian Genetic Diseases Network, a nationwide partnership program, isolated mouse retinal stem cells from a small pigmented area near the front of the eye called the ciliary margin. Placed in a culture, the cells differentiated into retinal components, including photoreceptors and bipolar neurons. The activity took place without the need for growth factors, which suggests that an inhibitory mechanism works naturally to keep retinal stem cells in check. Investigators are now trying to identify those inhibitory factors with the hope of one day being able to turn them off and thus repair damaged retinas. The work appears in the March 17 *Science*. *—P.Y.*



CNRI/PHOTOTAKE

Retinal cells

HISTORY OF SCIENCE

Atomic Dead Letter

Werner Heisenberg is known not only for his uncertainty principle in physics but also for his uncertain motives in directing the Nazi atomic program. In 1941 he visited his former mentor Niels Bohr in occupied Copenhagen, but why? Did he wish to persuade Bohr that a Europe ruled by Germany would not be so bad, or did he seek to reassure him that the Nazis were not building an atomic bomb? The manifold possibilities are explored in Michael Frayn's critically acclaimed play *Copenhagen,* which made its U.S. debut on Broadway in April. Bohr never gave a public account of the conversation, but science historian Gerald Holton of Harvard University has revealed that the Danish physicist will speak from beyond the grave: the Bohr archives contain an unsent letter, from Bohr to Heisenberg, that was found in the pages of a book belonging to Bohr, Robert Jungk's *Brighter Than a Thousand Suns: A Personal History of the Atomic Scientists*. According to Holton, Bohr "takes strong exception" to Heisenberg's account of the meeting as published in the book. Alas, we ordinary folk will not be permitted to know the full contents of the letter until 2012, on the 50th anniversary of Bohr's death. *—Graham P. Collins*

AIP/NIELS BOHR LIBRARY

Heisenberg and Bohr, Copenhagen, 1934

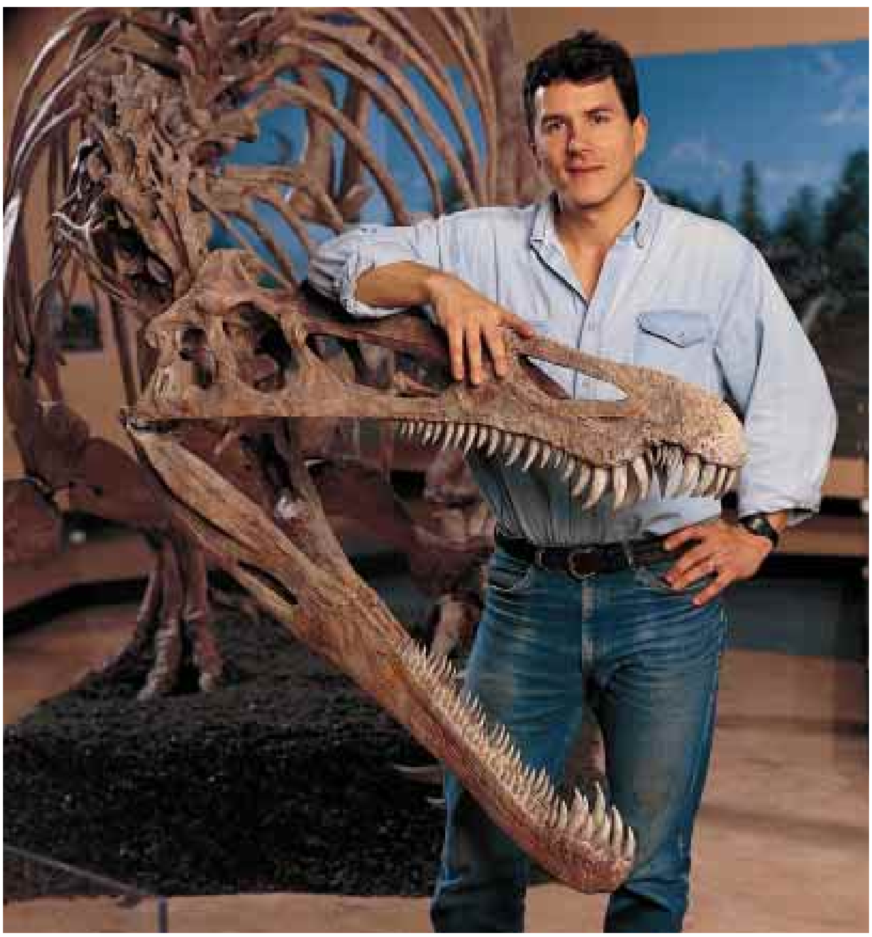
DINOSAUR HUNTER_PAUL C. SERENO

Paleontology's Indiana Jones

From digging to designing, this celebrity scientist has helped map the evolution of dinosaurs

CHICAGO—Paul C. Sereno can't talk to me when I arrive on a Friday morning in early March. The University of Chicago paleontologist is busy preparing the lecture for a class that starts in 10 minutes. So I sit silently in a chair opposite him, taking in the ferocious-looking saber-toothed tiger skulls, dinosaur claws and other paleontological curiosities that perch atop the bookcases lining his spacious, sunlit office. Moments later he springs out of his seat, collecting the notes and transparencies. "It's been a hectic morning," he says hurriedly, explaining that he forgot his notes at home, as we head downstairs to pick up some slides. Realizing now that he's left something in his office, Sereno dashes back up the stairs two at a time. Within seconds he races down again, and we're off to class at a similarly aerobic pace.

Although it comes with a certain amount of chaos, such abundant energy has served the 42-year-old Sereno well in his prolific career as dinosaur hunter, scholar and popularizer. He has explored remote regions of South America and Africa and turned up numerous dinosaur skeletons (about a dozen of which represent new species)—discoveries that have elucidated such murky issues as the origins of dinosaurs and the effects of continental drift on their evolution.



RAISING *SUCHOMIMUS*: Paleontologist Paul C. Sereno designed the skeletal mount for this predatory dinosaur, which he discovered on his most recent expedition to Niger.

There was a time, however, when such accomplishments seemed unlikely. Born and raised in Naperville, a western suburb of Chicago, to an artist and a civil engineer, Sereno was the second of six children. But unlike his siblings, he performed poorly in school. In fact, by sixth grade he was nearly flunking. "I couldn't imagine finishing high school," he says.

Fortunately, once Sereno actually entered high school he discovered something he loved, something he was good at: art. Driven by his newfound aspiration, he settled down. "I started studying during my lunch hours to make up the ground," he recounts. Eventually improving his entrance exam scores dramatically, he was accepted at Northern Illinois University, where he planned to become an artist.

He studied painting, favoring the detailed style of the 17th-century Dutch still-life artists. But during his junior year, on a trip to the American Museum of Natural History (AMNH) in New York City with his older brother, who was interviewing for graduate school, Sereno had an epiphany. At the end of their tour of the museum, he says, he knew he wanted to be a paleontologist, realizing he could combine his interests in art, science, travel and adventure. "I walked out of the museum and told them, 'You'll get my application next year.' "

Two years later, in 1979, Sereno entered Columbia University (which is affiliated with the AMNH), embarking on what would become a lifelong effort to understand the evolutionary relationships, or phylogeny, of the dinosaurs. The 1980s was an exciting time, he recalls. It marked the cusp of a revolution in systematics, and researchers were just beginning to sort out dinosaur anatomy and what it said about their family tree.

Then, in 1988, Sereno led his first expedition, to a remote Argentine valley in search of early dinosaurs. After three weeks of prospecting, their paltry research funds dwindling, he chanced on a skeleton that brought him to tears. Eroding out of the rock in a little corner that the team had nearly overlooked was a beautifully pre-

PHOTOGRAPHS BY RALF-FINN HESTOFT SABA

served specimen of one of the earliest dinosaurs ever discovered—a 228-million-year-old theropod dubbed *Herrerasaurus*. "I couldn't even look at it," Sereno remembers. "I thought it was going to disappear." A second field season at the site yielded an even more primitive beast, which they named *Eoraptor*.

Sereno gained some recognition for these early discoveries, but in recent years his has become one of the most recognizable names in the field. His approachable demeanor and youthful good looks have made him a media darling—even *People* magazine noticed, including the paleontologist in its "50 Most Beautiful People" issue in 1997. That same year *Newsweek* and *Esquire* put him on their own lists. Although he seems quite comfortable in the spotlight, Sereno acknowledges a downside. "Notoriety is a double-edged sword," he remarks, noting that it can convey what one is doing and so help research programs. But it can "engender a knee-jerk reaction on the part of other scientists," who suspect you have "sought every bit of attention that you are getting and are amplifying the importance of your work."

Such accusations may be difficult to substantiate, considering that Sereno's findings are consistently published in prestigious journals. In addition to describing multiple new dinosaurs, his research has called into question several hypotheses concerning the evolutionary history of these animals. For example, one popular theory holds that dinosaurs outcompeted rival groups in their rise to world domination. But after observing that many of the adaptations that served the beasts so well during their reign were already in place millions of years before they became common, Sereno has concluded that they merely took advantage of a vacant ecospace. He adds that he has found no evidence that coevolution between predators and prey, or between herbivores and flowering plants, drove the evolution of these animals, though these were previously thought to have been influential factors. Sereno's work has also shed light on the rate of change in the skeletons of dinosaurs—which started out as meter-long bipedal creatures and later diversified to include 36-ton quadrupeds.

(He is also eager to examine the dinosaur heart reported found in April. Medical imaging seems to reveal a four-chambered heart—bolstering the idea that dinosaurs are related to birds and were warm-blooded. Sereno has publicly expressed doubts that soft tissues could have been preserved in the South Dakota sediment from which the fossil was unearthed in 1993 and would like to look for other coronary features.)

Recent inquiries stem largely from discoveries made in Africa, where Sereno has led four expeditions since 1990. The trips are grueling and often dangerous,

BEAUTY AND THE BEAST: Sereno puts the finishing touches on *Jobaria*, a newly named sauropod.

because some dig sites are in politically unstable areas, yet paleontology's Indiana Jones remains unfazed: "The question is, How much danger is there relative to the danger we live with on a daily basis?" But he points out that such exotic fieldwork isn't for everyone. "For a lot of people it seems like a romantic thing, but when you get out in the Sahara that romance wears off after about two days. And then you realize, Wow, it's hot! And you've got to dig *that* up?"

"That," in a 1997 expedition to Niger, included 20 tons of bone representing a giant new kind of sauropod dubbed *Jobaria*. "At one point the bone was 151 degrees [Fahrenheit], reflecting up into your face," Sereno remembers, adding that his 18-person team mapped and excavated that material, along with a *Tyrannosaurus rex*–size dinosaur called *Suchomimus* and a few tons of other specimens, loading and reloading the 25-ton cargo five times before reaching the coastal destination.

Sereno is particularly proud of the speed with which he has been able to bring the fossils out of the ground and into publication and displays. "We brought back all that rock [from Niger] at about the same time the Field Museum [in Chicago] bought Sue, the tyrannosaur," he notes. Yet months before Sue was unveiled in May, Sereno's team had already cleaned, cast and assembled three skeletons—comprising 17 tons of fossil material—for exhibition, in addition to publishing its findings in *Science*.

Of course, drive isn't the only requirement. There remains the pesky problem of funding, which the team ran out of before completing the skeletons. As luck would have it, the Chicago marathon was coming up, so Sereno decided to run in it to raise money for his project. And, though he had never run a marathon before, he managed to win the celebrity challenge (which also took an on-line popularity vote into consideration) with a time of three hours and 16 minutes, in the end raising $15,000 for his dinosaurs.

Such close involvement with these projects stems partly from Sereno's belief in the power of presentation. "I consider visual things just as important as the words you put down," he states. "I think that's why people understand as much as they do about what we're doing." But he also seems to delight in these activities. He's currently designing an M. C. Escher–inspired cover for a monograph on *Eoraptor*. "I've been able to fit Pangaea, the home of *Eoraptor,* in between *Eoraptor*s," he enthuses. "I've divided up the space so that if you move in one direction you see *Eoraptor* emerging, and if you move in the other direction you see the continents dividing. It's called '*Eoraptor* and the Division of an Ancient Plane.'"

In his nonacademic time Sereno devotes himself to "getting kids to take themselves seriously." Several years ago he and his wife, educator Gabrielle H. Lyon, started a nonprofit science outreach group called Project Exploration, which aims in part to set troubled children from the Chicago public schools on new trajectories by getting them interested in science. Among the group's programs is a mini expedition out West. Being outside in a totally different place, thinking about the ancient past and finding a fossil bone fragment, Sereno observes, can really have an effect on these kids. "I come from totally believing in the potential of people," he declares. "I'm absolutely, fundamentally convinced that most of us will never understand the various talents we have because we never test ourselves enough." —*Kate Wong*

MATERIALS SCIENCE_NANOENGINEERING

Tantalizing Tubes

Hype aside, applications for carbon nanotubes progress—slowly

If good things come in small packages, then the tiniest packages should harbor the best things. Such is the thinking surrounding carbon nanotubes, a name that reflects their nanometer-scale dimensions. Discovered in 1991 by Sumio Iijima of NEC Corporation, carbon nanotubes are an exotic variation of common graphite. The tubular structure imparts mechanical and electronic properties that have raised the eyebrows of dozens of researchers at universities and commercial concerns around the world. The short list of attributes includes super strength, combined with low weight, stability, flexibility, good heat conductance, large surface area and a host of intriguing electronic properties.

The possibilities have led to breathless accounts of existing or potential real-world applications. For example, articles have hailed a company's use of alleged nanotubes as polymer additives to promote electrostatic adhesion of paint on car parts; the carbon in question is actually a grosser graphite that forms long fibrils. Other press reports have noted that nanotubes could be the fiber that finally makes earth-tethered satellites possible. Considering that the longest-known nanotubes are on the order of one millimeter, thoughts of a 35,800-kilometer-long nanotube rope are still a bit premature. These exaggerations aside, researchers have begun understanding and even exploiting nanotubes, particularly in electronics and in materials science.

Carbon nanotubes are descendants of buckminsterfullerene, or "buckyball," the soccer-ball-shape molecule of 60 carbon atoms. Despite the initial enthusiasm for applications, the roundest of round molecules has yet to see commercialization. As one wag in *The Economist* put it, "The only industry the buckyball has really revolutionized is the generation of scientific papers." Most research into applications has gravitated to the nanotubes, composed of hexagons of carbon atoms and looking very much like a miniature version of rolled-up chicken wire. (In reality, the tubes form not by furling sheets of graphite but by the self-assembling propensity of carbon atoms for knitting together, like yarn making a sweater sleeve, under various sets of extreme conditions.)

Shortly after nanotubes were discovered, Noriaki Hamada of NEC and Mildred S. Dresselhaus of the Massachusetts Institute of Technology independently uncovered an unusual twist, literally. They calculated that if a row of hexagons going down the tube's long axis were straight, the tube should behave as a metal and conduct electricity. If a line of hexagons formed a helix, however, the tube should act as a semiconductor. Both predictions were ultimately confirmed.

The electronics potential has become the most ballyhooed application for carbon nanotubes, in large part because silicon's future may be less bright than its past. "It is predicted that in 10 years or so, there may be bottlenecks appearing in the further improvement of silicon devices," explains Phaedon Avouris, manager of the nanoscale science and technology group at the IBM Thomas J. Watson Research Center. Continuing miniaturization of silicon components and fine control of electronic properties at smaller scales may soon pose intractable problems. So the electronics industry has begun looking for workable alternatives [see "Computing with Molecules," by Mark A. Reed and James M. Tour, on page 86]. "One of the possibilities is to base technology on a completely different element," Avouris states. "And in that case, carbon is the best bet." As the basic unit of organic chemistry, carbon is extremely well understood, a notion that comforts many researchers.

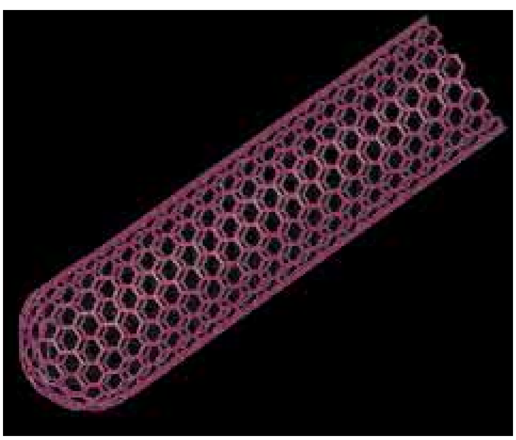
The past couple of years have seen promising demonstrations in carbon nanotube electronics. In 1998 both Avouris and Cees Dekker of the Delft University of Technology in the Netherlands showed that a single nanotube could act as a transistor. Last year, with Leon Balents of Lucent Technologies, Dekker reported that a single nanotube, with a natural junction where a straight section joined to a helical section, behaved as a rectifying diode—a half-transistor in a single molecule. Avouris has shown that the current flowing through a semiconducting nanotube can be changed by more than five orders of magnitude. "So," he observes, "it's a good switch."

Such virtuosity has electronics people understandably excited—but the road to sophisticated nanotube devices will be a long one. The work by Dekker and Avouris involves so-called single-wall nanotubes. "If you're going to make circuits, you have to organize the tubes," explains Thomas W. Ebbesen of the Nanostructure Laboratory at Louis Pasteur University in Strasbourg, France. "And every tube has a different property, depending on diameter and helicity. You can't even selectively grow one tube or another now." These challenges mean that development is a long way from reality. The only techniques currently available for bulk production form a mass of mixed types, including tubes within tubes, called multiwalled nanotubes, which have less well defined characteristics. For delicate electronics experiments, single-walled tubes of specific helicities must be painstakingly mined.

Fortunately, not all electronic applica-

Some Possible Uses for Carbon Nanotubes

- **Transistors and diodes**
- **Field emitter for flat-panel displays**
- **Cellular-phone signal amplifier**
- **Ion storage for batteries**
- **Materials strengthener**



RICHARD E. SMALLEY *Rice University*

COURTESY OF SAMSUNG ADVANCED INSTITUTE OF TECHNOLOGY

FLAT SCREEN using carbon nanotubes as the source of phosphor-exciting electrons may compete with LCDs in a few years.

tions need to be so elegant. Even messy mixtures of multiwalled tubes are good at field emission—they emit electrons under the influence of an electrical field. And field emission is the force behind flat-panel displays. A deep-bellied television or computer monitor relies on a big gun to shoot electrons at the pixels of a phosphor screen, which light up as ordered. Alternatively, millions of nanotubes arranged just below the screen could take the place of the gun. "Each pixel gets its own gun," explains David Tománek, a physicist at Michigan State University.

Several firms around the world are trying to exploit the nanotube talent in flat-panel displays. Researchers at the Samsung Advanced Institute of Technology in Suwon, South Korea, led by Won Bong Choi, appear to be in the lead. "Last Christmas they had a nine-inch display, and I could see baseball players," Tománek relates. The prototype required half the power of conventional liquid-crystal displays, and the nanotubes appear to meet the 10,000-hour lifetime typically demanded of electronics components. Zhifeng Ren of Boston College has produced neat forests of multiwalled nanotubes directly on glass surfaces, showing the potential of growing nanotubes in place, with the screen as substrate.

The issue for displays then becomes the orderly operation of all those nanotubes. "You have the complexity of now needing a separate circuit for every single pixel," points out Philip G. Collins, also of IBM's nanoscale group. Experts in conventional electronics need to find solutions to these intricate wiring problems before nanotube displays can become commonplace.


CSIRO MOLECULAR SCIENCE

STARSTRUCK: Researchers with CSIRO, the Australian organization for scientific and industrial research, have demonstrated that they can lay down nanotubes in patterns. Such control is critical for applications like flat-panel displays.

Nanotubes emit electrons at a relatively low voltage, which translates to minimal power requirements, while maintaining high current densities. These characteristics encouraged Otto Z. Zhou, a physicist at the University of North Carolina at Chapel Hill working with colleagues at Lucent, to try to generate microwaves via nanotube field emission, with implications for wireless communications. Cellular phones typically send a weak signal to a local base station, where microwave amplifiers beef up that signal.

"In principle, you could make the base station smaller, with a longer working life, thanks to the stability of the nanotubes," Zhou says. "We have a prototype that generates microwaves, the first time that that has been demonstrated in an electron emission material."

The battery designers are also keeping an eye on nanotubes. Graphite can store lithium ions, the charge carriers for some batteries, but at a weighty price: six carbon atoms for every lithium ion. Researchers speculate that the geometry inherent in bundles of nanotubes allows them to accommodate more than one lithium per six carbons. "It would be nice if you could access both the inside and the outside of the cylinder," remarks John E. Fischer, a materials scientist at the University of Pennsylvania, referring to both the insides of carbon nanotubes as well as the gaps between tightly packed tubes. "That's the leitmotif that runs through all research using nanotubes for anode materials," he adds.

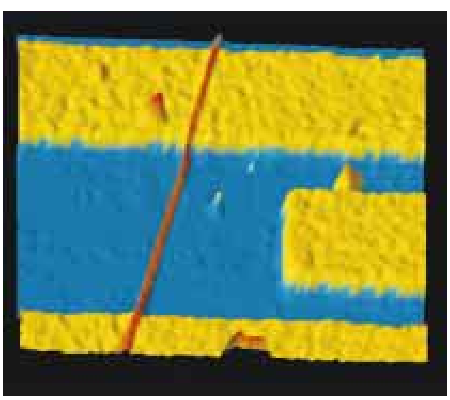
The holy grail in this world is probably hydrogen storage. The target for hydrogen capacity that would interest electric-car manufacturers is about 6.5 percent by weight, in whatever storage medium is used. Dresselhaus, writing in the *Materials Research Society Bulletin* last November, pointed out that various claims exceeding 6.5 percent have been difficult to reproduce. She notes that 4 percent by weight of hydrogen is the best figure available and that increasing it to the benchmark "represents a significant technological future challenge."

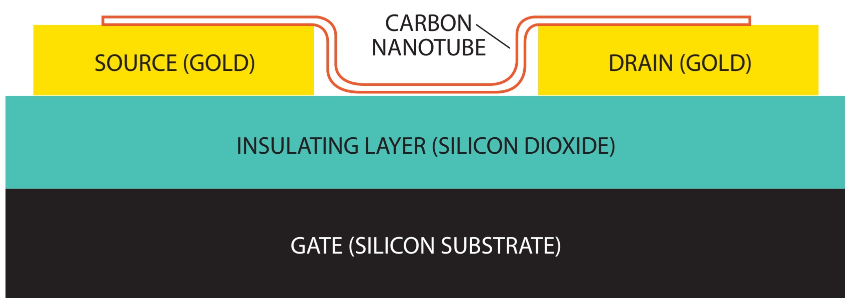
The other major arena for the small tubes is in materials. Nanotubes are about six times lighter and 10 times stronger than steel at the same diameter. But that's an awfully small diameter. "The strength of a nanotube is something that people have talked about quite a lot," says materials scientist Paul D. Calvert of the University of Arizona. "But in the end, the strength that counts is the strength of the thing you make out of it." Carbon fiber is already a proven winner in composite materials, and carbon nanotubes certainly have promise in the same market because of their exceptionally high length-to-diameter ratio, the vital figure in stress transmission. But there are miles to go to fulfill that potential. At a January meeting, Calvert recounts, "the nicest statement was from a group that demonstrated that carbon nanotubes do not degrade the properties of the epoxy resin. In other words, we can make something that's no worse than if we didn't put the tubes in at all."

One of the biggest boosters of future materials applications is the National Aeronautics and Space Administration, which hopes to find a place for nanotubes in everything from spacecraft to space suits. "But we have to figure out how to get the properties that are now on the nanoscopic scale up to something that we can use on a macroscale," says Bradley Files of the NASA Johnson Space Center of the nanotubes' low weight and high strength. "Every pound counts."

So does every dollar. "What concerns me is getting the cost down," Ebbesen says. Right now nanotubes run about 10 times the price of gold. With its relatively deep pockets, NASA may play a crucial role in all nanotube research. "We'd like to push the whole field," Files remarks. "We can't do all the work ourselves, and we see such breakthrough possibilities with the technology." Basic studies that uncover the secrets to growing specific types of tubes could also accelerate research and lower the cost.

Even if nanotubes fail to revolutionize the world directly, the research with them should still prove valuable, especially in tomorrow's advanced electronics. "They provide a great training ground for understanding electrical properties and behavior at very small dimensions," Avouris says. "Because one way or another—through nanotubes or through silicon or through other so-called molecular electronics—we're going to get there." —*Steve Mirsky*





SEMICONDUCTING CARBON NANOTUBE, 1.5 nanometers in diameter (*left*), can be incorporated into a field-effect transistor, channeling current between the source and drain when an electrical field is set up by a voltage applied to the gate.

PHAEDON AVOURIS *IBM Thomas J. Watson Research Center*

Accounting for Taste

OAKLAND—Personal taste is notoriously tricky to quantify. Opinions are subtle. Nonlinear. And just barely associative. "Taste is idiosyncratic," says Ken Y. Goldberg of the University of California at Berkeley, who studies the subject as a computer software problem. "The best example is that you don't always like all of your friends' friends."

But most of the time, you do. And thanks more to reason than RAM, one long-hyped method of automated recommendation is finally proving itself. Called collaborative filtering, it predicts individual preferences based on the preferences of others. Amazon.com rolled out one of the first commercial applications of collaborative filtering in 1997, recommending books that your nearest neighbors in taste, as determined by their click history, have bought. Its filtering engine was designed by Net Perceptions, which also built CDNow.com's system. Net Perceptions was co-founded by the "father of collaborative filtering," John Riedl, a computer scientist at the University of Minnesota, who in 1994 co-authored a paper on the collaborative filtering of newsgroup postings.

Although the first publicly accessible academic experiments were novel and showed promise, it has taken some time to shake out the kinks. All too often, Amazon's book suggestions proved to be so general or off-base that you'd have had better luck throwing darts at the *New York Times Book Review*. Firefly, an early music recommender, was fun to fiddle with, but you were just as well off (if not better) chatting up the music fiend behind the counter at the nearest Tower Records.

Naturally, the engines grew smarter as ever more Internet users fed them with data. But the software engineers grew smarter as well, developing novel algorithms, customization features and more user-friendly interfaces. An important innovation was tuning the engines. An early customer, Riedl recalls, was an on-line grocer that expected collaborative filtering to expand the scope of what customers put in their shopping carts. Not quite. "They called and said, 'We don't need your fancy software package to tell us that our customers like bananas,' " Riedl says. The solution was to enable clients to adjust the software themselves to recognize items that are already big sellers and "recommend others that are more of a surprise."

Now researchers are pushing personalization further. In Riedl's university lab, Jon Herlocker invented a feature to appear on the MovieLens site, which will translate the reasoning behind a recommendation into a language the user can understand and respond to. For instance, MovieLens might recommend *Titanic* if your neighbor in the profile database enjoyed it. Then, if you watch it and give it a thumbs down, MovieLens will provide you with the option of shutting out the opinions of that anonymous neighbor.

Unfortunately, most people haven't used sites enough for their profiles to be sufficiently developed, says Dan Greening of Macromedia eBusiness Solutions, makers of the LikeMinds collaborative filter engines used at Levis.com, WeddingNetwork.com and other sites. The key, Greening believes, is that his software is elitist when determining who is dropped in the "mentor pool" of user profiles that are actually mined for recommendations. Good mentors have rated many things over a wide spectrum, making them general "opinion leaders." But if they also prove to be good mentors for other mentors in the pool, the lesser candidates will be flushed out.

While Greening has been coding the makings of a good mentor, Goldberg and his colleagues have taken a different approach, using pending patents accrued from their joke-recommending site, Jester. They founded PreferenceMetrics; its demonstration site, Sleeper, is eerily accurate at recommending books based on ratings of books users may not have even read. The site polls you on your level of interest in a particular book, given a brief description. Accuracy is also increased because your user profile is determined only by the ratings you actively provide; other sites don't distinguish between items you buy for yourself and those you choose for others.

Sleeper's recommendations are based on an algorithm that employs a mathematical technique called principal component analyses to lower the number of variables, or dimensionality, of the problem. That speeds up the software's recommendation process without compromising accuracy, according to Goldberg.

But the unique and most noticeable element in Sleeper is its continuous rating bar. Traditionally users pick from a five-level rating system, like a newspaper's movie reviews. Goldberg's rating bar spans from "very interested" to "not interested," enabling the user to click anywhere in between. The computer translates the clicked position into a number between 1 and 500. Taste is more visceral than rational, Goldberg says, and "moving the mouse along the bar feels a lot more kinesthetic than the rational process of clicking on buttons."

Most of today's collaborative-filtering Web sites are based on "personalizing" a retailer's relationship with a customer because, as Riedl bluntly puts it, "that's where the money is." But Riedl, along with Greening and Goldberg, are optimistic that as the technology continues to improve, myriad applications will follow. They predict that their brainchild will imminently return full circle to its roots as an information filter and become, Riedl maintains, "one of the most important changes in the way information is disseminated." Goldberg agrees, pointing out that customization of what you see on your monitor is increasingly mandatory as the screens on emerging Internet portals, cellular phones and wearable computers continue to shrink.

Yet whatever the access point is, one of the ultimate hopes of collaborative filtering is that on-line individuals will each have their own intelligent agents, crawling the network and seeking out news you can use before you even ask for it. After all, in some sense, your agent may know you even better than you do. —*David Pescovitz*

DAVID SUTER

WAGING A NEW

KIND OF WAR

What could possibly be new about war? People have always been quite imaginative about finding ways to impose their will by violent force. Rocks and spears, catapults and muskets, mustard gas and nukes: you might think that human civilization has tried it all. Evidently not.

Over the past decade or so, the norms of war have decisively shifted. Gone is even the semblance of order, the traditional view of war as two opposing forces wearing uniforms and meeting at front lines. Anarchy is no longer merely part of war; it is war. The rifles, land mines and machine guns of recent or ongoing conflicts in Bosnia, Colombia, Congo, East Timor—in a fourth of the countries in the world—can wipe out the infrastructure of a nation and the moral order of a society as surely as a nuclear bomb. Civilians are targets as much as combatants, often more so. Defenders loot the very people they claim to protect, and then flee. Children fight alongside adults. The front line may be someone's bedroom. Hospitals and libraries are fair game. Even humanitarian aid workers become pawns.

Amid the chaos, scholars have identified several factors common to modern conflicts. As arms-control experts Jeffrey Boutwell and Michael T. Klare discuss in the first article of this special report, most of today's battles are fought not with tanks and fighter jets but with machine guns and mortars—weapons that have become increasingly available since the end of the cold war. In some places, guns and grenades now cost less than a family meal. Their proliferation reinforces a disquieting trend of the past century: as historians Walter C. Clemens, Jr., and J. David Singer document, civilians account for an ever increasing fraction of the casualties of war.

Psychiatrist Richard Mollica describes how his profession is only now coming to terms with the emotional toll that modern war has on civilian populations. Mental illness on a massive scale makes it hard to rebuild once the fighting ends. In a recent study, a fourth of Bosnian refugees were so traumatized that they could not work or take care of their families. Finally, psychologist Neil Boothby and humanitarian program officer Christine Knudsen report on their work with child soldiers, boys and girls younger than 18 who are press-ganged by armed groups and brainwashed into becoming killers. Can these young people ever rejoin society? The answer remains uncertain.

These articles do not just chronicle the savagery; they outline what might be done about it. Early in the 20th century, war in Europe seemed never-ending, and East Asia appeared destined to remain an economic backwater. The battles of the post–cold war world are no more inevitable. For all the hand-wringing about "ancient hatreds," the natural tendency in any society is toward moderation; the vast majority of people just want to get on with their lives. The international community can tip the balance back in their favor by stemming the flood of guns that inundates these countries, by taking clear stands on war crimes, by providing help with psychological as well as physical reconstruction, and by redoubling assistance with economic development. —*George Musser and Sasha Nemecek, staff writers*

MOSTAR, BOSNIA-HERZEGOVINA, MAY 1993: A Croat soldier fires from the bedroom window of an abandoned apartment building. The front line between Croat forces and the Bosnian army ran down the main thoroughfare of the city.

JAMES NACHTWEY *Magnum*

A SCOURGE OF

With a few hundred machine guns and mortars, a small army can take over an entire country, killing and wounding hundreds of thousands

ACHOY-MARTEN, CHECHNYA, DECEMBER 17, 1994: A group of Chechens armed with a variety of rifles and other light weapons, including a World War II–era grenade, a grenade launcher and a bazooka, take cover a few hours before war breaks out.

EAST NEWS SABA

Most media accounts of the 1994 Rwandan genocide emphasized the use of traditional weapons—clubs, knives, machetes—by murderous gangs of extremist Hutu. As many as one million Tutsi and moderate Hutu perished, many of them women and children. To outsiders, it appeared as if the people of Rwanda had been caught up in a violent frenzy, with common farm implements as their favored instruments of extermination.

But this isn't the whole story. Before the killing began, the Hutu-dominated government had distributed automatic rifles and hand grenades to official militias and paramilitary gangs. It was this firepower that made the genocide possible. Militia members terrorized their victims with guns and grenades as they rounded them up for systematic slaughter with machetes and knives. The murderous use of farm tools may have seemed a medieval aberration, but the weapons and paramilitary gangs that facilitated the genocide were all too modern.

The situation there was far from unique. Since the end of the cold war, from the Balkans to East Timor and throughout Africa, the world has witnessed an outbreak of ethnic, religious and sectarian conflict characterized by routine massacre of civilians. More than 100 conflicts have erupted since 1990, about twice the number for previous decades. These wars have killed more than five million people, devastated entire geographic regions, and left tens of millions of refugees and orphans. Little of the destruction was inflicted by the tanks, artillery or aircraft usually associated with modern warfare; rather most was carried out with pistols, machine guns and grenades. However beneficial the end of the cold war has been in other respects, it has let loose a global deluge of surplus weapons into a setting in which the risk of local conflict appears to have grown markedly.

The cold-war-era preoccupation with nuclear arms and major weapons systems has left those of us in the arms-control community with very little knowledge about the global trade in small arms (technically, pistols, revolvers, rifles and carbines) and light weapons (machine guns, small mortars, and other weapons that can be carried by one or two people). Over the past few years, however, many of us have begun to examine why these weapons are so easily accessible and how they affect the societies now flooded with them. The disturbing findings are driving a new arms-control movement, led by a loose coalition of the United Nations, concerned national governments and nongovernmental organizations.

Small arms and light weapons are weapons of choice in most internal conflicts for a number of reasons: they are widely obtainable, relatively cheap, deadly, easy to use and easy to transport. Unlike major conventional weapons, such as fighter jets and tanks, which are procured almost exclusively by national military forces, small arms span the dividing line between government forces—police and soldiers—and civilian populations. Depending on the gun laws of a particular counby Jeffrey Boutwell and Michael T. Klare

SMALL ARMS

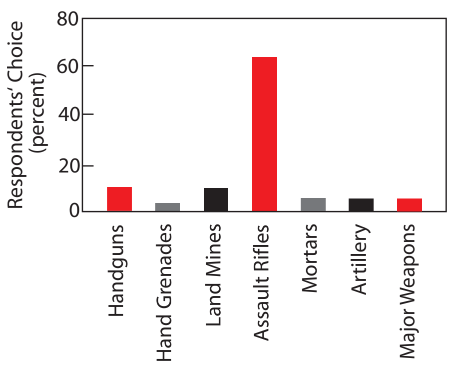
try (if such regulations even exist or are enforced), citizens may be permitted to own anything from pistols and hunting guns to military-type assault weapons.

In contrast to the declining trade in major weaponry since the end of the cold war, global sales of small arms and light weapons remain strong. No organization, private or public, provides detailed data on the global trade in these weapons, in part because of the difficulty of tracking so many transactions (and because of the low level of attention that has been paid to the problem). Reliable estimates of the legal trade in small arms and light weapons put the annual figure between $7 billion and $10 billion. A large but unknown quantity of small arms—worth perhaps $2 billion to $3 billion a year—is traded through black-market channels. Because data are so scarce, comparing these numbers to those for small-arms exports during the cold war is difficult. But studies in southern Africa and the Indian subcontinent do indicate that during the 1990s the availability of modern assault rifles increased considerably.

Governments transfer vast quantities of small arms, either through open, acknowledged military aid programs or through covert operations. And as the size of their militaries has dwindled, Western and ex-Communist countries have sold off their excess weapons to almost any interested party. Most arms, though, are sold by private firms on the legal market through ordinary trade channels. Although such sales are supposedly regulated, few countries pay close attention. The U.S. probably has some of the strictest controls, but even so, it sold or tranferred $463 million worth of small arms and ammunition to 124 countries in 1998 (the last year for which such data are available). Of these countries, about 30 were at war or experiencing persistent civil violence in 1998; in at least five, U.S. or U.N. soldiers on peacekeeping duty have been fired on or threatened with U.S.-supplied weapons.

We have few data on the quantity or dollar value of small arms sold by other manufacturers. Based on existing weapons inventories of military and police forces around the world, though, certain major suppliers can be identified: Russia (maker of the AK-47 assault rifle and its derivative, the AK-74), China (maker of an AK-47 look-alike known as the Type 56 rifle), Belgium (FAL assault rifle), Germany (G3 rifle), the U.S. (M16 rifle) and Israel (Uzi submachine gun).

Common small arms such as the AK-47 are cheap and easy to produce and are extremely durable. Manufactured in large quantities in more than 40 countries, they can be purchased at bargain-basement prices in many areas of the world. In Angola, for instance, a used AK-47 can be acquired for as little as $15—or a large sack of maize. Cost is a crucial factor: many of the belligerents in these internal battles are poor and have often been barred from the legal arms market. As a result, they consider cheap small arms and light weapons, perhaps traded illegally, to be their only option.



MOST DESTRUCTIVE WEAPONS are assault rifles, according to Red Cross workers asked to describe which arms caused the most civilian casualties.

The proliferation of automatic rifles and submachine guns has given paramilitary groups a firepower that often matches or exceeds that of national police or constabulary forces. Modern assault rifles can fire hundreds of rounds of ammunition per minute. A single gunman can slaughter dozens or even hundreds of people in a short time. With the incredible firepower of such arms, untrained civilians—even children—can become deadly combatants. Unlike the weapons of earlier eras, which typically required precision aiming and physical strength to be used effectively, ultralight automatic weapons can be carried and fired by children as young as nine or 10 [see "Children of the Gun," on page 60].

Although the figure of $10 billion spent on small arms and light weapons each year may seem insignificant when compared with the roughly $850 billion spent annually on military forces around the world, the money for light weapons has had a hugely disproportionate impact on global security. In addition to ravaging so many countries, the arms have

LAURIE GRACE; SOURCE: "ARMS AVAILABILITY AND THE SITUATION OF CIVILIANS IN ARMED CONFLICT," ICRC 1999 REPORT

Supply and Demand

Only a few countries supply most of the world's small arms and light weapons. The types shown here are among the most common available today. Their light weight and deadly firepower make them ideal for use by poorly trained soldiers, including children. The chart lists 50 conflicts; information on child soldiers and leading arms suppliers is noted where available.

LEADING SMALL-ARMS SUPPLIERS

BELGIUM (BE)	ISRAEL (IS)
BRAZIL (BR)	ITALY (IT)
BULGARIA (BU)	RUSSIA (R)
CHINA (C)	SOUTH AFRICA (SA)
FRANCE (F)	U.K. (UK)
GERMANY (G)	U.S. (US)

M16 (and similar models)

Used in **67** countries
Main manufacturer: **U.S.**
Also made in four other countries, including South Korea and the Philippines
Total made: **8 million**
Weight: **6.4 lbs (2.9 kg)**
Caliber: **5.56 millimeter**
Rate of fire: **700–950 rounds per minute**

FAL rifle (and similar models)

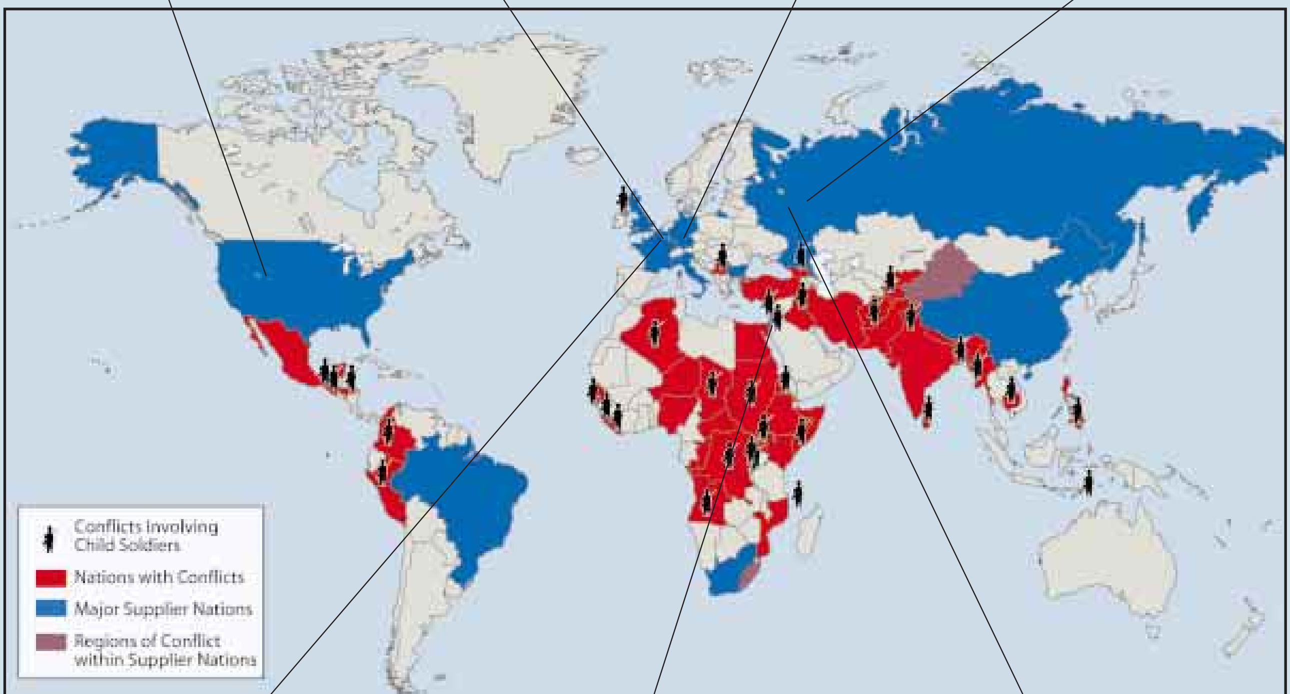
Used in **94** countries
Main manufacturer: **Belgium**
Also made in 11 other countries, including Argentina and Brazil
Total made: **5–7 million**
Weight: **9.5 lbs (4.3 kg)**
Caliber: **7.62 millimeter**
Rate of fire: **600–700 rounds per minute**

G3 rifle (and similar models)

Used in **64** countries
Main manufacturer: **Germany**
Also made in 12 other countries, including the U.K. and Turkey
Total made: **7 million**
Weight: **9.7 lbs (4.4 kg)**
Caliber: **7.62 millimeter**
Rate of fire: **500–600 rounds per minute**

AK-47 (and similar models)

Used in **78** countries
Main manufacturer: **Russia**
Also made in 11 other countries, including China and Egypt
Total made: **35–50 million**
Weight: **9.5 lbs (4.3 kg)**
Caliber: **7.62 millimeter**
Rate of fire: **600 rounds per minute**



MAG machine gun (and similar models)

Used in **81** countries
Main manufacturer: **Belgium**
Also made in seven other countries, including the U.S. and India
Total made: **150,000 (from Belgium alone)**
Weight: **24 lbs (11 kg)**
Caliber: **7.62 millimeter**
Rate of fire: **650–1,000 rounds per minute**

Uzi (and similar models)

Used in **42** countries
Main manufacturer: **Israel**
Also made in China and Croatia
Total made: **Unknown**
Weight: **7.7 lbs (3.5 kg)**
Caliber: **9 millimeter**
Rate of fire: **600 rounds per minute**

RPG-7 grenade launcher (and similar models)

Used in at least **40** countries
Main manufacturer: **Russia**
Also made in six other countries, including China and Iran
Total made: **Unknown**
Weight (with sight): **14 lbs (6.3 kg)**
Grenade caliber: **85 millimeter**

SOURCES: Jane's Infantry Weapons, 2000–2001; *and* Military Small Arms of the 20th Century (7th ed.); *weight listed is for unloaded weapons.*

REGIONS IN CONFLICT

REGION IN CONFLICT IN 1998, 1999 OR 2000	SOLDIERS AND REBELS UNDER 18		KNOWN WEAPONS SUPPLIERS
	TOTAL NUMBER	LOWEST AGE	
AFGHANISTAN	100,000+*	10	R
ALGERIA	100+*	15	R
ANGOLA	7,000+	8	R, F, US, private dealers
BANGLADESH	100+	16	
BURUNDI	8,000+	8	private dealers
CAMBODIA	7,000*	5	F, R, C, SA
CENTRAL AFRICAN REP.	NONE		
CHAD	NOT KNOWN	12	US, F
CHECHNYA	1,000+*	11	
CHINA	NONE		
COLOMBIA	19,000+	8	US, G, R
COMOROS	NOT KNOWN	13	
CONGO (Brazzaville)	NOT KNOWN	14	IT, black market
CONGO (Kinshasa)	6,000+	7	C, F, US
EAST TIMOR	1,000+	15	US, UK, G, F, R, domestic
EGYPT	NONE		US, F
ERITREA	100+	11	
ETHIOPIA	NOT KNOWN	12	
GEORGIA	NONE		
GUATEMALA	1,000+*	11	
GUINEA-BISSAU	50+	17	
HAITI	NONE		
HONDURAS	1,000+*	13	
KASHMIR	100+*	12	C, R, UK, F, G, US, domestic
KENYA	NONE		US, BE
KOSOVO	100+*	13	
KURDISTAN (Iraq, Iran, Turkey)	3,000+	7	F, C, BR, US, G, R, IT, IS, UK, dom.
KYRGYZSTAN	NONE		
LEBANON	100+*	9	
LESOTHO	NONE		
LIBERIA	12,800*	6	
MEXICO	1,000+*	6	
MOZAMBIQUE	NONE		
MYANMAR	50,000+	6	C, domestic
NEPAL	NONE		
NIGER	NONE		
NIGERIA	NONE		
NORTHERN IRELAND	NOT KNOWN	16	
PALESTINE (Occup. Territories)	1,000+*	12	
PERU	2,100+	9	R, US
PHILIPPINES	1,000+	10	US, UK, domestic
RWANDA	20,000+	7	C, IS, SA, US
SENEGAL	NONE		
SIERRA LEONE	5,000+	5	US
SOMALIA	1,000+*	11	
SOUTH AFRICA	NONE		US, IS, F, UK, G, dom.
SRI LANKA	1,000+*	8	C, US, IS, black market
SUDAN	25,000+	7	C, F
TAJIKISTAN	100+*	16	R
UGANDA	8,000+	5	US, R

** 1996 estimate (Other figures are for 1998–2000.)*

SOURCES: Amnesty International, Coalition to Stop the Use of Child Soldiers, Forum for Applied Research and Public Policy, Project Ploughshares, Swedish Save the Children

drastically increased the demands placed on humanitarian aid agencies, U.N. peacekeepers and the international community. To cite but one statistic, international relief aid for regions in conflict increased fivefold during the 1990s, to a high of $5 billion a year. At the same time, long-term development aid dropped overall. Short-term remedies have replaced more lasting cures for the worst ills of poverty, deprivation and war. Moreover, armed militias equipped with but a few thousand assault rifles have erased the benefits of billions of dollars and years of development effort in many poor countries.

From 100 Men to the Presidency

Nowhere has the relation between the accessibility of light weapons and the outbreak and severity of conflict been more dramatically evident than in West Africa. Liberia was the first to suffer. On Christmas Eve in 1989, insurgent leader Charles Taylor invaded the country with only 100 irregular soldiers armed primarily with AK-47 assault rifles; within months, he had seized mineral and timber resources and used the profits to purchase additional light weapons. Had he needed to equip his forces with heavier weapons such as artillery, armored cars and tanks—the weapons conventionally associated with a conquering army—Taylor would have faced crippling logistical obstacles. In comparison, a few boatloads of assault rifles, rocket-propelled grenades and machine guns were simple to transport and provided more than enough firepower. In 1990 Taylor's ill-trained and undisciplined insurgents toppled the government of President Samuel Doe (who had come to power in a conventional, albeit bloody, coup 10 years earlier). Fighting continued for seven more years.

The firepower of modern small arms—and the rapid escalation of violence that such weaponry makes possible—was evident even in the early stages of Liberia's civil war. In August 1990, in retaliation for Ghana's participation in a West African peacekeeping force (which had tried but failed to stop the fighting), Taylor's troops slaughtered 1,000 Ghanaian immigrants in one day in the Liberian village of Marshall. Likewise, forces loyal to Doe massacred 600 ethnic Gio and Mano—Liberian groups that favored Taylor—as they vainly sought refuge in a church in the capital city, Monrovia.

Sierra Leone was next. In 1991 Taylor and a disgruntled army officer from Sierra Leone, Foday Sankoh, initiated an informal alliance. Soon weapons and fighters were flowing back and forth across the border between the two countries. By 1999 the civil war in Sierra Leone had claimed the lives of more than 50,000 people, while another 100,000 had been deliberately injured and mutilated. Only in the summer of 1999 did the combined efforts of the U.N. and West African peacekeepers prove successful in helping to broker a peace agreement—an agreement that included a campaign to collect and destroy former combatants' weapons.

The current peace efforts in Sierra Leone and Liberia remain tenuous and highly dependent on what happens to the tens of thousands of weapons now in these countries. By October 1999 the disarmament program in Liberia had destroyed some 20,000 small arms and light weapons and more than three million rounds of ammunition. Across the border in Sierra Leone, however, U.N. officials complain that former rebels surrender to peacekeepers without also turning in their weapons, despite a $300 cash incentive to relinquish their guns. Unfortunately, this inability to disarm former combat-

ILLUSTRATIONS BY LAURIE GRACE

ants has led to renewed outbreaks of fighting during the past several months.

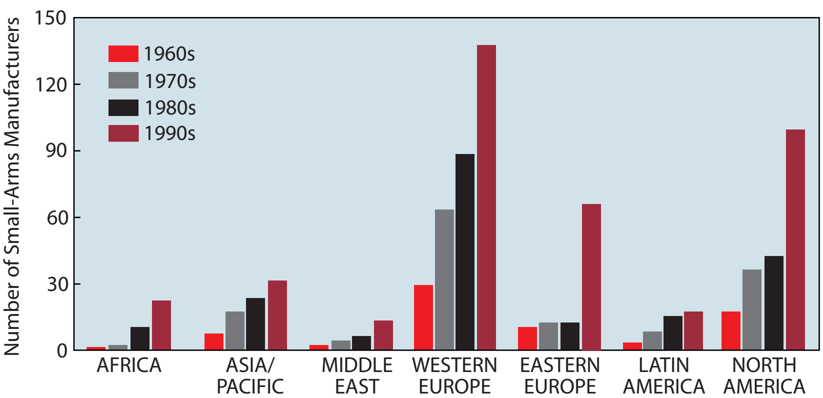
Much the same cycle of violence engulfed Rwanda—but on an even more horrific scale. The majority Hutu government and the minority Tutsi opposition both had been amply supplied with small arms and light weapons. France, Egypt and South Africa outfitted the government; Uganda and China equipped the Tutsi-dominated Rwandan Patriotic Front (RPF). While government forces held off the RPF with mortars and machine guns, Hutu militiamen armed with guns and machetes slaughtered up to one million Tutsi and moderate Hutu in May and June of 1994. The genocide ended only when most Tutsi in Rwanda had been killed or had fled to areas controlled by the RPF.

Similar acts of brutality routinely characterize today's ethnic and sectarian violence. Once competing groups have been armed with automatic weapons, any minor dispute can escalate quickly into a major bloodbath. And the availability of such weapons, even in remote and inaccessible places such as southern Sudan and eastern Congo, makes it difficult for the international community to bring the warring parties to the bargaining table—and, when a cease-fire is signed, to curb the cycle of bloodletting. Brokering peace has proved especially difficult in countries such as Angola and Sierra Leone, where rebel forces have been able to exchange diamonds or other commodities for guns and ammunition on the black market.

The Corrosive Effect of Guns

The root causes of ethnic, religious and sectarian conflicts around the world are of course complex and varied, typically involving historical grievances, economic deprivation, demagogic leadership and an absence of democratic process. Although small arms and light weapons are not themselves a cause of conflict, their ready accessibility and low cost can prolong combat, encourage a violent rather than a peaceful resolution of differences, and generate greater insecurity throughout society—which in turn leads to a spiraling demand for, and use of, such weapons.

In 1998, in a comprehensive survey of the problem of small-arms proliferation, the International Committee of the Red Cross (ICRC) noted its deepening concerns about this issue, particularly regarding the safety of civilians. As a leading guardian of international humanitarian law, the ICRC stated that it was especially troubled by three dangerous trends. First, the group expressed its alarm at the growing number of civilian deaths and injuries—which often reach 60 to 80 percent of total casualties—that occur in modern conflicts. Equipped with rapid-fire automatic weapons, untrained and undisciplined fighters, few of whom know anything of the Geneva Conventions on human rights, either specifically target civilians or fire indiscriminately into crowds, killing and wounding scores of noncombatants, including women and children.



MORE COMPANIES MAKE SMALL ARMS today than ever before. A survey of the number of private companies in the business of small-arms production over the past four decades shows how the market expanded at the end of the cold war.

LAURIE GRACE; SOURCE: "MANUFACTURING TRENDS: GOING TO THE SOURCE," PETE ABEL IN *RUNNING GUNS*, EDITED BY LORA LUMPE (ZED, LONDON, 2000)

Second, civilians now suffer increased pain and deprivation when international relief operations must be suspended more frequently because the aid workers themselves have become targets of attack. In the 1990s more than 40 ICRC personnel were killed in Chechnya and Rwanda alone, compared with the 15 who lost their lives in all conflicts between 1945 and 1990.

Third, societies awash in weapons often find themselves caught in a culture of violence even after the formal conflict ends. For young ex-combatants who have known little else besides war, their weapons become a status symbol and a means of making a living, either through individual acts of street crime or as part of an organized criminal operation.

By conducting interviews with its field personnel and by analyzing medical data collected during its operations in Cambodia and Afghanistan, the ICRC has been able to document the high rates of civilian death and injury caused by small arms and light weapons, both during armed combat and after the fighting had stopped. In looking at the data from Afghanistan, for example, researchers found that weapons-related injuries decreased by only one third after the civil war ended and that gunshot fatalities actually increased. In many postconflict societies, up to 70 percent of all civilians still possess military-type firearms, mainly assault rifles such as the M16 and AK-47. ICRC personnel indicate that these weapons are responsible for more than 60 percent of all weapons-related deaths and injuries in internal conflicts—far more than land mines, mortars, grenades, artillery and major weapons systems combined. From El Salvador to South Africa, the story is depressingly similar: years of internal conflict are followed by high rates of social and criminal violence made possible by the easy access to small arms and light weapons.

Faced with the chaos and devastation wrought by the influx of small arms and light weapons, political leaders are now beginning to push for their control. In July 1998 representatives of 21 countries (including the U.S., Brazil, the U.K., Germany, Japan, Mexico and South Africa) met in Oslo and agreed to work together to curb the proliferation of these weapons. The U.N. has also called on member states to tighten their munitions-export regulations and to cooperate in efforts to suppress illicit trade in small arms. But although there is widespread agreement that something must be done, there is considerable uncertainty as to what. Nevertheless, arms experts and others are beginning to devise practical and enforceable methods for controlling the small-arms trade.

Proponents of small-arms control have largely abandoned the goal of enacting a single, all-encompassing instrument like the land-mine treaty. When signed in 1997, that treaty seemed a natural model for an agreement that would prohibit most exports of small arms and light weapons. But eliminating all transfers of small arms between states would never receive the support of those countries that depend on imported weapons for their basic military and police requirements. Many states, including China and Russia, also view guns as legitimate items of commerce and are thus reluctant to embrace any measures that would restrict their trade. Accordingly, the favored approach emphasizes a multidimensional effort aimed at eliminating illicit arms transfers and imposing tighter controls on legal sales, along with promoting democratic reform and economic development in poor, deeply divided societies.

Setting Sights on Arms Control

No widely accepted blueprint describes how to accomplish such broad goals. Arms-control experts have agreed, however, on five basic principles. First, timely information on global trafficking in small arms must be made available for the identification of dangerous trends (such as the buildup of arms stockpiles in areas of instability) and for the facilitation of local or regional curbs on imports. Some data on small-arms deliveries are now made public by individual suppliers—the U.S. and Canada have been particularly forthcoming in this regard—but at present there is no international system of reporting. The only existing mechanism of this kind, the U.N. Register of Conventional Weapons, covers major weapons only.

Second, major military suppliers should adopt strict standards for the export of weapons through legal channels. Although the manufacture of small arms and light weapons is widely dispersed, a dozen or so countries are responsible for the bulk of arms sold on the international market. These include the five permanent members of the U.N. Security Council—the U.S., Russia, China, the U.K. and France—plus a number of other European, Asian and Latin American countries. If these countries could agree to a common system of restraints on exports, the sale of arms to areas of instability should fall substantially. Some weapons would still flow through clandestine channels, but most large-scale transactions would be subject to international oversight.

Third, no system that regulates the supply of arms can be entirely effective without an effort to dampen the global demand for arms, especially in areas of recurring conflict. Significant progress has been made in this direction in West Africa, the locale of several of the most pernicious conflicts of the 1990s. In 1998, under the prodding of Alpha Oumar Konaré, the visionary president of Mali, the Economic Community of West African States (ECOWAS) adopted a three-year moratorium on the import, export and manufacture of small arms and light weapons. This moratorium represents the first time that a bloc of states that import large numbers of light weapons has adopted a measure of this kind and stands as an important model that other regions can emulate. Already member states of the Southern African Development Community (SADC) have considered such a step; a group of East African states met in Kenya in March to discuss a similar enterprise.

Fourth, efforts to control the legal trade will have only limited effect unless steps are taken to eradicate the black-market trade in arms. The Organization of American States (OAS) has been especially active in working to curb this trade. Recognizing the close link between illicit arms sales, drug trafficking and violent crime, the members of the OAS adopted a convention in 1997 that requires member states to criminalize the unauthorized production and transfer of small arms and to cooperate with one another in suppressing the black-market trade. (The U.S. has signed the treaty, but the Senate has not yet ratified it.) The Clinton administration is pushing to have similar measures incorporated into the Transnational Organized Crime Convention, now being negotiated in Vienna, to make them applicable in every region of the world. To promote further cooperation in this area, the U.N. plans to convene a conference on illicit arms trafficking next summer.

Finally, as U.N. peacekeepers in Angola, Rwanda, Somalia and elsewhere have learned, peace agreements must help reintegrate former combatants into the civilian economy, or fighters are likely to drift into careers as mercenaries, insurgents or brigands—taking their guns with them. The collection and destruction of used and surplus weapons is perhaps the most challenging aspect of the small-arms problem. Nevertheless, individual states and nongovernmental organizations have begun to devise and test possible solutions such as weapons "buy-back" programs. The European Union and the World Bank have also promised to assist in the development of job-training programs and other services for ex-combatants seeking to reenter civil society in war-torn areas of Africa and Latin America.

RURAL COLOMBIA, APRIL 9, 1994: Members of the CRS insurgency group, a splinter group of the ELN, or National Liberation Army, turn in weapons as part of a government-run program.

RICHARD EMBLIN *Black Star*

None of these measures by itself can overcome the dangers posed by the uncontrolled spread of small arms and light weapons. The problem is far too complex to be solved by any single initiative. Yet each time international leaders have sought to enact controls on nuclear, chemical or biological arms, they have dealt with similar problems. The foundation has now been laid for the world to bring small arms under effective control. If we fail, we are likely to face even greater bloodshed and chaos in the decades ahead. SA

The Authors

JEFFREY BOUTWELL and MICHAEL T. KLARE are co-directors of the Project on Light Weapons at the American Academy of Arts and Sciences and co-editors of *Light Weapons and Civil Conflict* (Rowman and Littlefield, 1999). Boutwell is associate executive officer at the American Academy of Arts and Sciences, where he heads the program on international security studies. Klare is a professor of peace and world securities studies at Hampshire College and is director of the Five College Program in Peace and World Security Studies.

INVISIBLE WOUNDS

Medical researchers have recently begun to address the mental health effects of war on civilians

by Richard F. Mollica

The Khmer Rouge executed her entire family. Their beatings left her unconscious, lying on the bodies of her loved ones. When my first Cambodian patient told me this story in graphic detail in 1981, my initial reaction was that it simply couldn't be true. It seemed so unreal, like a scene taken straight from a horror movie. My instinct was to disbelieve.

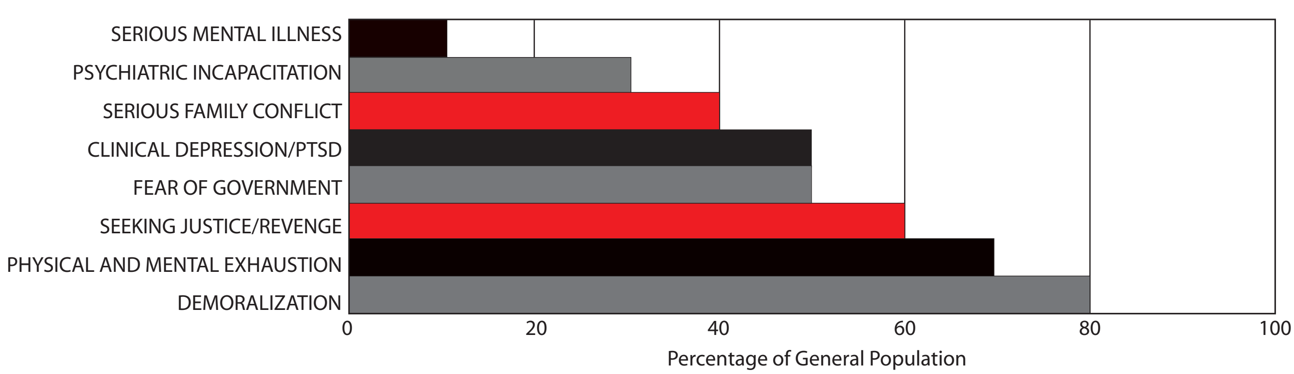
My feeling was an example of what novelist Herman Wouk has called "the will not to believe." Such a response is a common reaction to accounts of human cruelty and emotional suffering, and it is one of the reasons that political leaders, humanitarian aid workers and even psychiatrists have failed to appreciate the depth of war's trauma. The model used to be a rubber band. War is hell, but we thought that once a conflict ended, those affected would snap back to normal. Physical injuries would linger, but the anxiety and fear that accompany any life-threatening event should disappear once the immediate danger passes. The general public had much the same attitude. In essence, the message from the outside world to war's victims was: Be tough. Just get over it.

Indeed, that was the thinking about most traumatic events, from child abuse to rape. Now we know better. Awful experiences can cause damage that does not always heal naturally; the victims may need counseling, economic assistance and medication. Post-traumatic stress disorder (PTSD) was officially recognized in 1980, partly because of the experience of U.S. veterans of the Korean and Vietnam wars. But it has only been in the past two decades that researchers have documented the social and emotional consequences of war for civilian populations. These findings are revolutionizing the recovery of societies devastated by war.

In 1988 our team at Harvard University, with the support of the World Federation for Mental Health, sent a psychiatric team to Site 2, the largest Cambodian refugee camp on the Thai-Cambodian border. We interviewed 993 camp residents, who recounted a total of 15,000 distinct trauma events, such as kidnapping, imprisonment, torture and rape. Yet the international authorities charged with protecting and providing for the camp had made no provisions whatsoever for mental health services. Similar lapses affected other refugee operations the world over. Over time the reason became clear: the mental health effects of mass violence are invisible.

Put simply, it is easier to count dead bodies and lost limbs than shattered minds. Wounded people readily seek out doctors, but the stigma of mental illness is high, so traumatized people typically avoid psychiatrists at all costs. The lack of standardized criteria for mental health disorders and the differences among cultures have also contributed to the neglect. Local folk diagnoses may not match the disease categories of Western medicine.

The survivors of mass violence often keep their feelings to themselves because they fear misunderstanding—with good reason. In his memoirs, Primo Levi describes the fantasies he had while at Auschwitz. He dreamed of seeing his family again but also dreaded it: "It is an intense pleasure, physical,



NEARLY EVERYBODY in a society at war is traumatized to some degree, ranging from serious mental illness (such as psychosis) to clinical depression and post-traumatic stress disorder. According to these composite statistics from recent civil wars, the vast majority of civilians are exhausted, despairing and mistrustful, which wrecks the social fabric for a generation or longer.

inexpressible to be at home, among friendly people and to have so many things to recount; but I cannot help noticing that my listeners do not follow me. In fact, they are completely indifferent; they speak confidently of other things as if I were not there. My sister looks at me, gets up and goes away without a word—the grief is unbearable."

People's disbelief and disinterest are unfortunately quite real. They reflect the problem we all have in comprehending evil. How can human beings perpetrate such acts? Lacking a simple answer—and wishing to avoid our own intimations of guilt—we change the subject.

When international agencies finally began to address mental health, they first sought simple solutions. Yet providing mental health care is even less straightforward than rebuilding roads or treating malaria. Nevertheless, researchers have made headway; six basic discoveries point the way.

The first is the sheer prevalence of major psychiatric disorders among civilian survivors of war. Advances in psychiatric epidemiology—random samples of representative populations, utilization of lay interviewers and development of standardized criteria for diagnosis, even across cultures—have at last yielded reliable numbers. Our study of Cambodian refugees revealed levels of acute clinical depression and PTSD of 68 and 37 percent, respectively. Roughly similar numbers have been found among Bhutanese refugees living in Nepal and among Bosnian refugees living in Croatia. By comparison, in nontraumatized communities rates of 10 percent for depression and 8 percent for PTSD (over a lifetime) would be considered high.

Second, researchers have determined that the nature of the trauma can be rigorously measured. Psychiatrists used to worry that probing a patient's traumatic experiences would be too emotionally disturbing. They also felt that patients would provide inaccurate accounts, at best exaggerated and at worst outright lies. But beginning in the early 1980s, a new movement emerged in medicine, associated with the activities of groups such as Amnesty International. Human-rights researchers developed a systematic method that combines various types of clinical examinations to verify the accuracy of reports.

DRAGOBIL, KOSOVO, OCTOBER 28, 1998: A group of ethnic Albanian women weep over the body of Ali Murat Pacarizi, a 20-year old Kosovo Liberation Army soldier killed while trying to defuse a Serbian booby trap.

ENRIC MARTI *AP Photo*

For instance, our clinical service found that psychiatric patients from Indochina who had suffered horrific brutality were unable to describe their experiences in a standard open-ended psychiatric interview. Instead we tried a simple screening instrument known as the Hopkins Symptom Checklist, which has been widely used in general populations since the 1950s. The list takes about 15 minutes to fill out and asks such questions as whether the respondent feels low on energy, has difficulty falling asleep or thinks about committing suicide. When we gave patients an Indochinese version of the checklist, they were able to relate their emotional reactions with little distress.

A Historical Perspective

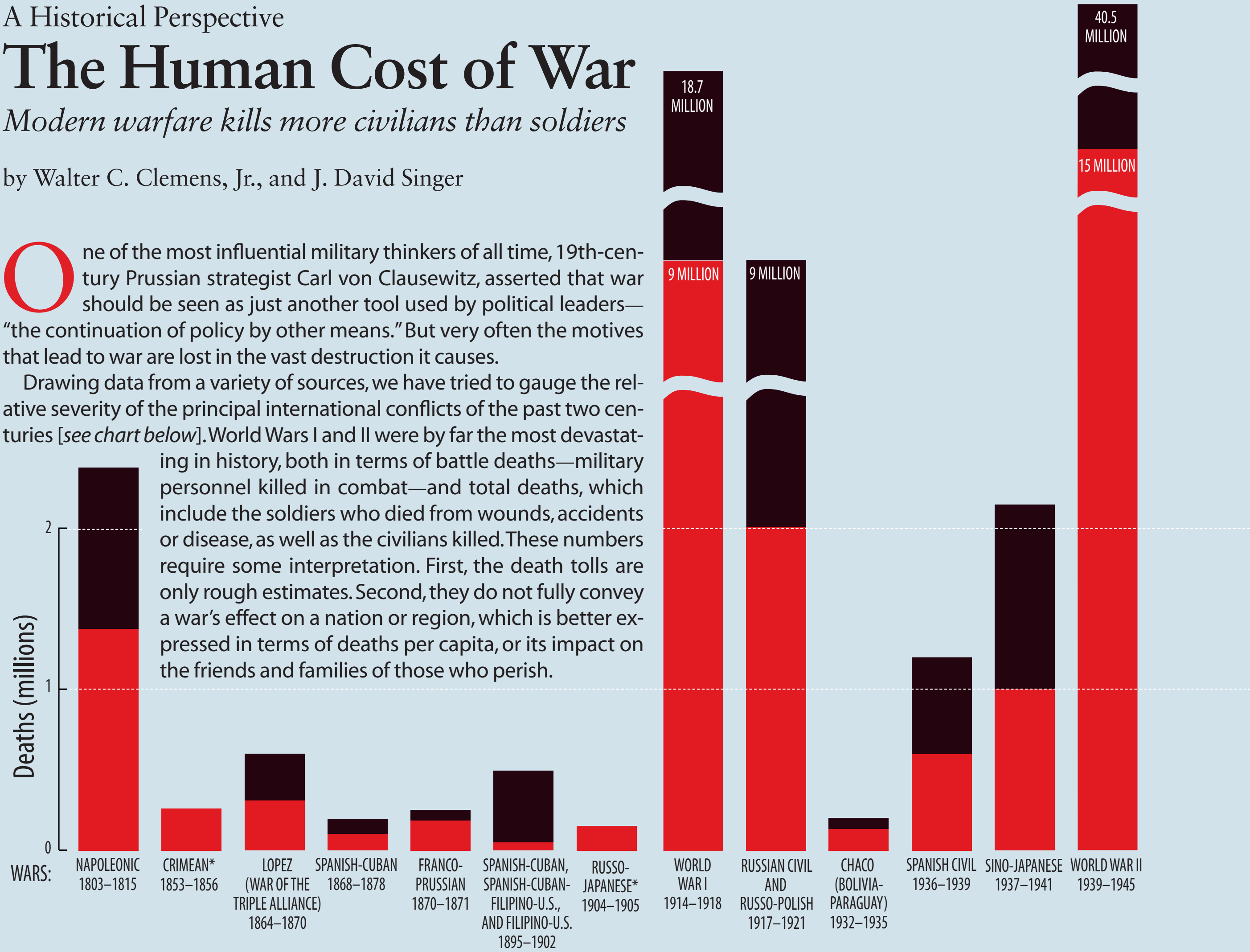
The Human Cost of War

Modern warfare kills more civilians than soldiers

by Walter C. Clemens, Jr., and J. David Singer

One of the most influential military thinkers of all time, 19th-century Prussian strategist Carl von Clausewitz, asserted that war should be seen as just another tool used by political leaders—"the continuation of policy by other means." But very often the motives that lead to war are lost in the vast destruction it causes.

Drawing data from a variety of sources, we have tried to gauge the relative severity of the principal international conflicts of the past two centuries [*see chart below*]. World Wars I and II were by far the most devastating in history, both in terms of battle deaths—military personnel killed in combat—and total deaths, which include the soldiers who died from wounds, accidents or disease, as well as the civilians killed. These numbers require some interpretation. First, the death tolls are only rough estimates. Second, they do not fully convey a war's effect on a nation or region, which is better expressed in terms of deaths per capita, or its impact on the friends and families of those who perish.



A modified checklist, the Harvard Trauma Questionnaire, focuses on trauma events and symptoms of PTSD. It now exists in more than 25 languages, tailored for each unique cultural context and tested empirically.

Using the Right Idiom

Third, medical anthropologists have codified non-Western conceptions of mental health disorders. In many societies, traditional healers and community elders, rather than medical doctors, are the principal source of health care, particularly mental health care. But some patients fall through the cracks: traditional healers are not able to heal their condition, and doctors do not recognize their vague somatic complaints as symptoms of an underlying mental illness. Extensive fieldwork in Cambodia, Uganda and Zimbabwe has now catalogued the wide range of folk diagnoses associated with emotional suffering. Our team has produced an encyclopedia of these diagnoses for Cambodia, so that Western-oriented practitioners can identify mental illness using local idioms.

Fourth, particular traumatic experiences are more likely than others to lead to depression and PTSD. Among Cambodian refugees at Site 2, the most harmful incidents involved blows to the head, other physical injury, incarceration, and watching the murder or starvation of a child. Lacking shelter and witnessing violence to other adults had less of an impact.

Fifth, some of the most potent events cause permanent organic changes in the brain. In the early 1960s, Norwegian researcher Leo Eitinger and his colleagues discovered a link between head injury and psychiatric symptoms in the survivors of Nazi concentration camps. According to more recent research, the beatings suffered by American POWs during World War II and the Korean and Vietnam wars often led to brain damage. Similarly, of 200 civilian torture survivors examined by Danish researcher Ole Rasmussen and his colleagues, 64 percent had neurological impairments. Even in the absence of direct physical injury, emotional distress can scar the brain. The few available studies of subjects with PTSD have revealed that certain structures in the brain, such as the hippocampus, shrink as a result of trauma. Some neuroscientists have begun to connect these early results to the persistent and debilitating symptoms of PTSD.

The sixth and final discovery demonstrates the connection between mental distress and social dysfunction. Last year my colleagues and I analyzed the serious disability associated with psychiatric distress among Bosnian refugees living in

From the end of the Thirty Years' War in 1648 to the French Revolution in 1789, Europe's princes fought one another with relatively small armies. France's upheavals, however, gave birth to the concept of a "nation in arms." Starting at the same time, the Industrial Revolution turned cities and factories into prime targets. In most wars of the past century, civilian deaths have outnumbered military deaths. Some countries have lost more than 10 percent of their population in a single war (for instance, the Soviet Union during World War II). Americans have been largely spared by geography.

Since World War II, Asia, Africa and the Middle East have become the world's primary battlegrounds. In the conflicts that raged in Angola and Mozambique from the 1960s to the 1990s, more than 75 percent of the victims were civilians. A large number were also children: between 1985 and 1995, some two million children died from warfare, and another 10 million to 15 million were maimed physically or psychologically. One reason for the high civilian death rate is that many of the international conflicts since 1945 began as civil wars. The Korean, Vietnamese and Afghan wars, among others, started as internal conflicts but soon attracted outside intervention.

Amid the "new world disorder" of the 1990s, war often became a private enterprise. In the conflicts that followed the breakup of Yugoslavia, for example, much of the fighting was conducted by bands of irregulars who served out of personal loyalty, hope for booty or lust for revenge. Meanwhile U.S. armed forces began to do less fighting and more peacekeeping. The U.S. and its allies were able to minimize their own casualties in the war with Iraq in 1991 and in the Kosovo operation last year. Whether they can do so in future conflicts, however, is uncertain. Even von Clausewitz acknowledged the risk of "friction" during warfare—his euphemism for all the things that can go horribly wrong.

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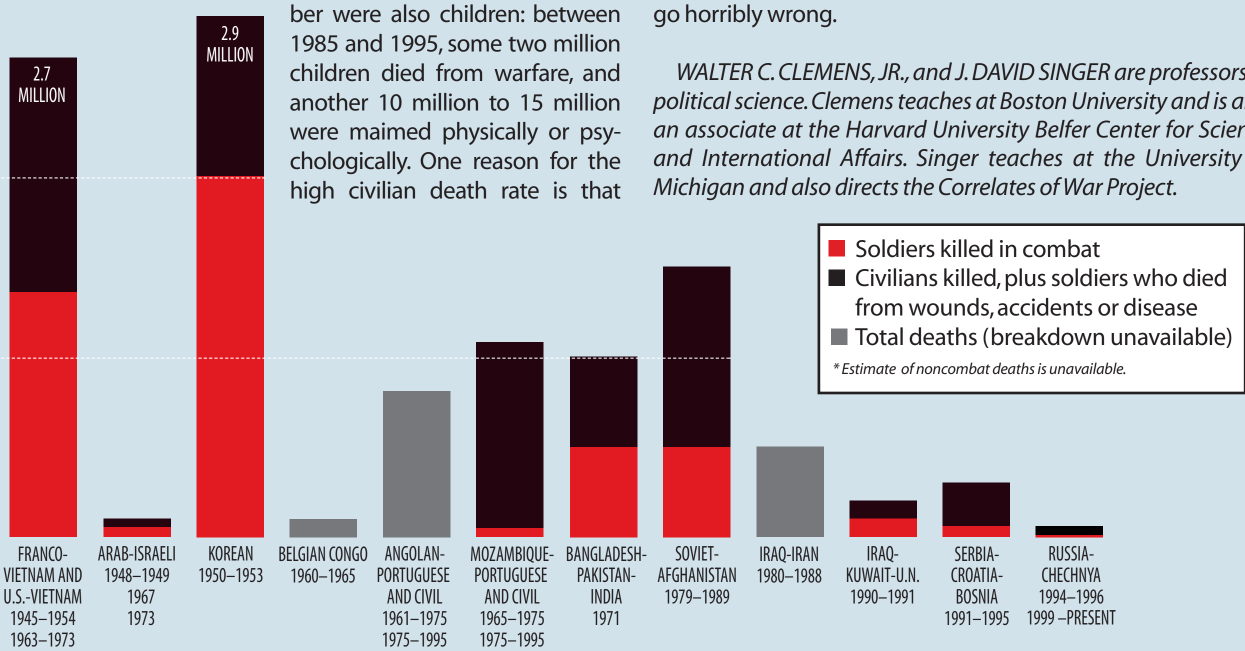


Croatia. One in four were unable to work, care for their families or participate in other socially productive activities.

The long-term effects of such a mental health crisis are still unknown; few longitudinal studies have been done. A recent survey of a Dutch population found that people who had been targets of Nazi persecution had a higher rate of PTSD over the subsequent 50-year period. Such traumas may have multigenerational effects as well: researchers have noted higher rates of PTSD in the children of Holocaust survivors compared with a nontraumatized Jewish comparison group. But the relation of cause and effect remains unclear. Did the Nazi horrors directly cause the PTSD, did they leave survivors vulnerable to subsequent traumas, or is the correlation related to some other variable altogether? To understand the long-term consequences of war, we are now conducting a longitudinal study in Bosnia.

The bottom line is that although only a small percentage of survivors of mass violence suffer serious mental illness requiring acute psychiatric care, the vast majority experience low-grade but long-lasting mental health problems [*see illustration on page 54*]. For a society to recover effectively, this majority cannot be overlooked. Pervasive physical exhaustion, hatred and lack of trust can persist long after the war ends. Like chronic diseases such as malaria, mental illness can weigh down the economic development of a country.

Only within the past five years have international organizations recognized this fact. The World Bank, in particular, has acknowledged that old development models are not working for war-devastated nations and that new approaches are needed. International aid agencies have established community-based mental health clinics in Cambodia and East Timor, and local doctors in South Africa and Bosnia have appeared on television to publicize the problems and opportunities for care. Our own program is now setting up microenterprise projects to ease depressed people back into productive work. Such efforts are crucial to breaking the vicious cycle of lethargy and revenge that blights an ever greater area of the globe. SA

The Author

RICHARD F. MOLLICA is a professor of psychiatry at Harvard Medical School. In 1981 he co-founded the Harvard Program in Refugee Trauma, one of the first clinical centers in the U.S. for survivors of mass violence and torture. This article emerged from a course he taught earlier this year at Waseda University in Tokyo.

LAURIE GRACE

CHILDREN

How do you make a child into a killer? Armed groups worldwide have developed a grim routine: abduct children from their families, inure them to abuse and "promote" them into combat

> The bandits killed my mother. And my brothers, too. They took me to their base camp. Yes, I was with the bandits. I had a gun. The chief taught me to use it. He beat me up. I had a gun to kill. I killed people and soldiers. I didn't like it.
>
> *—Boy in northern Uganda, aged six when abducted into antigovernment forces*

For military commanders in some of the poorest countries of the world, no strategy would be complete without children. They are more agile, impressionable and expendable than adult soldiers. They can stand watch at dangerous checkpoints, scout for mines and infiltrate enemy lines. Their natural empathy can be beaten out of them.

We would like to think that such attitudes are rare, isolated. The reality is different. Every day, all around the world, children are abducted and recruited into armed forces. An estimated 300,000 children are actively participating in 36 ongoing (or recently ended) conflicts in Asia, Europe, Africa, the Americas and the former Soviet Union. In Sierra Leone some 80 percent of all rebel soldiers are aged seven to 14. During the Liberian civil war from 1989 to 1997, seven-year-olds took part in combat. In the hostilities in Cambodia that nominally ended in the early 1980s, a fifth of wounded soldiers were between the ages of 10 and 14.

For most people, the term "child soldier" conjures up CNN television images of a teenage boy with an automatic weapon in hand. But in truth, both governmental forces and irregular armies use boys and girls as young as six. The younger children serve as spies, porters, cooks and concubines. As they get older, they may take up a weapon and enter combat. In some cases, children are snatched from their families; in other situations, they choose to join the armed group for their own protection and survival.

We have seen the magnitude and breadth of the problem of child soldiers in almost two decades of work in Afghanistan, Rwanda, Mozambique and Cambodia. Yet despite the widespread use of children under 18 as soldiers and recent advances in international law to prohibit the practice, the plight of these young people has never been mentioned in any peace agreement or demobilization scheme. In Mozambique, for instance, where a quarter of former soldiers in that country's 16-year civil war were recruited when they were younger than 18, the peace treaty offered no official recognition of the use of child soldiers. In fact, last year the government reinstated mandatory national military service. Those who were between seven and 13 years old during the civil war may well find themselves legally required to return to military life now.

The neglect has crippled the social and psychological development of a generation of children. Until eliminating the practice becomes a priority of international diplomacy, these societies may never be able to put the past behind them.

War as a Way of Life

Nearly all wars today take place in developing countries, where resources for health services and education are already limited. Of the 10 countries with the highest child mortality rate, seven are currently involved in a conflict or have been party to a conflict in the past five years. Every nation in sub-Saharan Africa either has been devastated by war or borders a nation that has been. Furthermore, these wars often last a generation or more, and children who grow up surrounded by war perceive it as a normal way of life.

In such unstable environments, young people are extremely vulnerable to recruitment into armed groups. They may become separated from family members when they are forced to flee their homes, and parents or other adult caregivers may be killed or conscripted, leaving children to fend for themselves. In many cases, joining an armed group or following an adult to the front lines may be their only options.

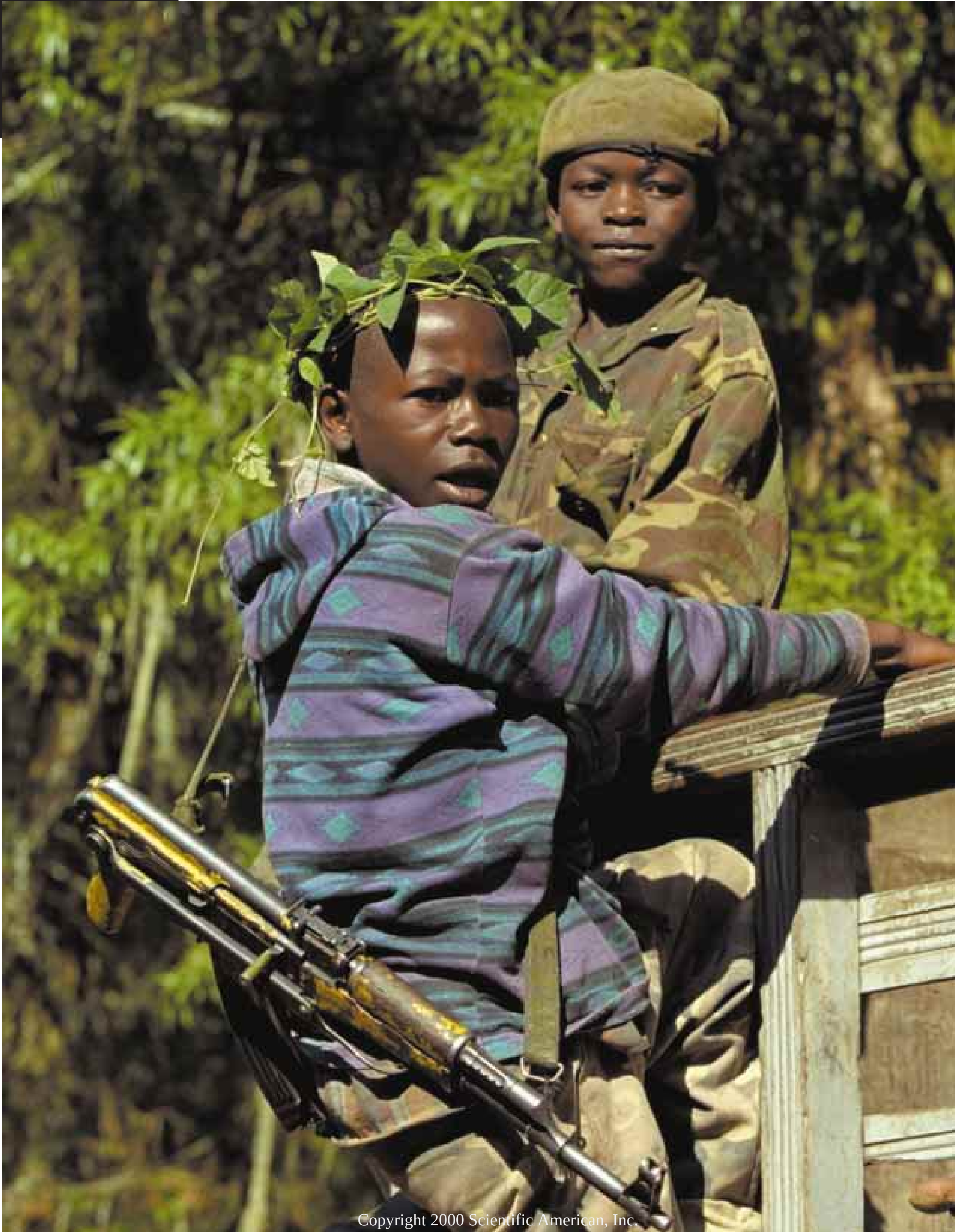
One young boy whom we met in the Democratic Republic of the Congo explained: "I joined [President Laurent] Kabila's army when I was 13 because my home had been looted and my parents were gone. As I was then on my own, I decided

BUTEMBO, ZAIRE, DECEMBER 11, 1996: Young members of the Mayi-Mayi militia, part of Laurent Kabila's rebel force, board a truck leaving for the front lines in eastern Zaire (now the Democratic Republic of Congo).

RICARDO MAZALAN *AP Photo*

by Neil G. Boothby and Christine M. Knudsen

OF THE GUN



to become a soldier." In Cambodia the United Nations found that most child soldiers either were orphans or came from very poor families; joining the army voluntarily was a ready means to get food and earn some money for any surviving relatives. Families may encourage their children to enlist as a chance for economic and social advancement. At times, teenagers seeking power and status will join armed factions on their own.

Even when children join armed groups "voluntarily," however, we must remember that they are really too young to fully assess risks or judge what is in their own best interests. Invoking a child's "right" to join an armed group is often no more than an excuse by those who wish to exploit the children for their own goals. The distinction between voluntary or forced recruitment of young people is essentially meaningless in many war zones.

Several thousand children each year over the past decade have been abducted or drafted by direct force, both by governmental and nongovernmental military groups. The most glaring examples today are in Sierra Leone and northern Uganda, where militias systematically kidnap children to increase their ranks and to terrorize communities. One 13-year-old girl from northern Uganda described her abduction: "It was tough. Some children who were too weak to walk were just chopped up with *pangas* [large knives] and left to die on the way. This scared me so much. In the bush I was allocated to a man to be his second wife. If you refused to show respect, you were beaten thoroughly."

APICHART WEERAWONG *AP Photo*

KA MAR PA LAW CAMP, MYANMAR, DECEMBER 6, 1999: Twelve-year-old Luther Htoo holds an M16 rifle as his twin brother, Johnny (*right*), watches. The Htoo twins lead God's Army, an ethnic Karen rebel group in the former Burma.

Indoctrination programs through the media and schools often precede both voluntary and forced recruitment efforts. During the Iran-Iraq conflict, thousands of 10- and 11-year-old boys on each side received instruction in martyrdom and were then marched off to their deaths carrying the keys their teachers told them would ensure entrance into heaven. In the 1980s Afghan leaders exiled in Pakistan viewed the lack of religious training among the general public as the main reason Communists had wrested control of their homeland. One Afghani resistance group opened a camp near Peshawar, where some 500 boys, mostly war orphans, were molded into the next generation of warriors. Teachers with rods in one hand and prayer beads in the other called on children to recite multiplication tables, the evils of Communism and what they would do when they grew up. "I am a little boy now, so I must study," one 10-year-old told us. "When I am big enough to hold a gun, I will join the holy war and avenge the murder of my father." The youngsters could not leave the camp until they were old enough to fight—typically, at age 13.

How to Unmake a Human Being

Our work in Mozambique from 1988 to 1995 provided considerable insight into how guerrilla groups socialize children into a life of violence. The program we established sought to reintegrate roughly 100 child soldiers into society. Two thirds of them had been abducted by Renamo, the Mozambique National Resistance. Once in the Renamo base camps, these girls and boys were expected to assist adult soldiers without question or emotion. Rewards included extra food, comfort and promotion from servant to bodyguard to combatant. Adults relied on physical abuse and humiliation as the main tools of indoctrination. One 14-year-old boy recalled: "Sometimes, just for their entertainment, the bandits forced children to fight each other in front of them. I was considered a good fighter because I was strong and I fought to win. [But] one time they forced me to fight against an adult, and he beat me."

In the first phase of indoctrination, Renamo members attempted to harden the children emotionally by punishing anyone who offered help to or displayed feelings for others subjected to abuse. One 12-year-old described how Renamo programmed him not to show fear: "They told us that we must not be afraid of violence or death and tested us to see if we could follow this command. Three different times people who tried to escape the base were brought back. The bandits brought all the children, including me, to witness their punishment. The bandits told us that we must not cry out or we would be beaten. Then a bandit struck the man in the top of the head with his ax."

By beating the children and exposing them to violence, Renamo conditioned them not to question the group's authority. Next, the group had to teach the children to become abusers themselves. In the words of a 12-year-old boy: "The bandits assigned other boys our age to watch over us. They were once part of our group and had also been beaten. Now they were

A Recent Phenomenon?
Come Children, Die

Whenever we discuss child soldiers, people often ask: Hasn't this been a problem from time immemorial? The answer is no. The practice of recruiting children has waxed and waned over the past millennium, but it has never played so large a role in warfare as it does today.

Under the feudal system of medieval Europe, only knights waged war. After a battle was lost and won, both sides disbanded and returned home. The chivalric code prohibited civilians from participating, and kings meted out drastic punishment to any nobleman who recruited peasants or children. The Catholic Church opposed the famous Children's Crusade in the 13th century, and the children never made it to Palestine, let alone engaged in battle. Outside the feudal system, wealthy burghers of the time, seeking private profit and territorial gains, recruited mercenaries, sometimes including boys. But the child soldier is really a product of the later era of standing armies.

The Prussian general Frederick the Great's words at Zorndorf in 1758, "Come children, die with me for the fatherland," were apt, as many of his soldiers were boys in their early teens. In 18th-century France the preteenage sons of poor nobility had little choice but to become career soldiers. The tide turned again at the end of the century during the French Revolution, when mass conscription became the norm and children were no longer needed as combatants. Even during the general mobilization of society near the end of the French Revolution, children worked exclusively with women and older men behind the scenes, tending to the wounded.

Up until the 1930s, wars were fought on battlefields between competing armies. Civilians were not the main targets, even though they suffered from hunger, looting and violence. The nature of warfare, however, changed drastically during the Spanish Civil War, in which airplanes bombed towns and cities. The ruthless destruction that began at Durango and Guérnica culminated when nuclear bombs killed 200,000 people at Hiroshima and Nagasaki in 1945. The unleashing of war on civilian populations rekindled the use of children as combatants. During World War II, several thousand children worked in resistance movements, valued for their resourceful ways and quick tempers. Children also took up arms in many of the colonial liberation wars of the 1950s and 1960s.

The modern movement to end child recruitment began with the efforts of Dorothea E. Woods of the Quaker United Nations Office in Geneva in the 1970s. Unfortunately, the problem has only worsened since then. In earlier conflicts, child combatants were bit players. But today they make up a large fraction of dozens of armed groups, and the abduction of children has become an instrument of terror.

In the mid-1980s the Norwegian branch of Save the Children developed one of the first modern rehabilitation programs for child soldiers. Located in Angola, it was foiled when an agreement with the Angolan military to demobilize the children fell through. Three years later the U.S. branch of Save the Children founded the first successful effort, in Mozambique. Today members of the international Save the Children Alliance have programs in Sri Lanka, Liberia and Sierra Leone; the Christian Children's Fund has one in Angola. Aid groups are considering new efforts in Colombia, Myanmar (formerly Burma) and Cambodia. Meanwhile hundreds of local groups in these countries struggle to address the crisis on their own. *—N.G.B. and C.M.K.*

put in charge and were even worse. They enjoyed hurting us. When one of us was caught doing something, the bandits made him stand in front of us. They asked us what the boy had done wrong. The first one of us to answer correctly was brought forward, too. He was given a stick or a bayonet to punish the other boy. The rest of us were told to answer quickly next time or we'd be beaten, too."

In some regions—Cambodia, Liberia, El Salvador—the grotesque initiation for child soldiers has included killing captives or even murdering their own family members. In Uganda the young people have been compelled to commit atrocities in their village at the time of recruitment, so that they have no easy escape route out of the armed group. From all accounts, these children were reluctant participants at first, but their initial feelings of fear and guilt were transformed under the watchful eyes of adult overseers. As one Khmer Rouge leader put it: "It usually takes time, but the younger ones become the most effective soldiers of all."

After two or three months in the camps, the Renamo children began combat training. In daily drills they learned to march, attack, retreat and shoot weapons. One 11-year-old boy recounted his military training: "Most of the boys were young and had not shot a gun before. The bandits taught us to take the gun apart and to put it back together. They lined us in rows and fired guns next to our ears so we wouldn't be afraid of the sound. Then they had us shoot the guns and kill cows. Boys who were the best at this were made chiefs of the group. When other people did something wrong, the bandits told these new chiefs to kill them. This is how boys became Renamo chiefs."

Light and easy-to-use automatic weapons make child soldiers as deadly in close combat as any adult soldier. Guerrilla insurgency tactics also play to their agility and pliability. In general, however, they make poor soldiers. They suffer much higher casualty rates than do their adult counterparts, in part because their lack of maturity and experience leads them to take unnecessary risks. In addition, children's bodies are more susceptible to complications if injured, and they are more likely to fall ill in the rough conditions of military camps: inadequate diet, lack of hygiene and health care, harsh training and physical punishments. Commanders typically view child soldiers as more expendable than adults, so they receive less training and must undertake the most dangerous tasks, such as checking for minefields or spying in enemy camps.

Children No More

Human-rights advocates know little about the fate of children who partake in mass violence. Common sense might suggest a moral breakdown, but this does not always appear to be the case. In Northern Ireland, researchers have discovered that children's social and moral concepts are resilient; family bonds and religious values remain strong in the face of violence. Similar results have emerged from studies in South Africa. During the long fight against apartheid, many children there outfoxed security forces and were sometimes directly involved in violent confrontations with police or members of rival communities. These same children, however, generally maintained an essential distinction

SRINAGAR, KASHMIR, MARCH 1991: Young children affiliated with the rebel movement in Kashmir display AK-47 assault rifles and a grenade launcher (*left*).

T.A. DAVIS *SABA*

between violence for just and unjust causes (although in recent years psychologists have noted an increasing tendency toward gang activities and violence in South Africa). In a 1986 study of how children form political beliefs, Harvard University psychiatrist Robert Coles argued that social crisis can even stimulate a precocious moral development in some children.

For the children we observed in Mozambique, the length of time spent in base camps—more than the extent of personal involvement in violence—dictated a child's subsequent moral response. In general, children who had stayed less than six months appeared to emerge with their basic trust in traditional values intact. Even though some had committed acts of violence, they continued to define themselves as victims rather than as members of Renamo. After liberation, most of these young people did initially display aggressive behavior and distrust of adults. But these actions and attitudes subsided quickly, and their early recovery efforts were marked more by post-traumatic stress disorder and remorse than by antisocial behavior.

On the other hand, children who had spent one year or longer in Renamo camps appeared to have crossed some kind of threshold. Their own self-concept had become solidly entwined with their captors. The conditions were so adverse and Renamo's indoctrination so persistent that these young people had come to view themselves as members of the group. As one 15-year-old boy put it: "I was reborn in that base camp. Even if I could escape, I never could have gone home again. Not after what I had seen and done." Out of context this statement might sound like an expression of remorse, but the young man was simply speaking factually.

Most of these children could articulate the belief that the generalized use of violence was "wrong," but they continued to use it as their principal means of exerting social control and influence. One 13-year-old told us that Renamo was not concerned with people's well-being; instead the group used people "like animals" to achieve its objectives. He went on to say that he thought this was wrong. The next afternoon, however, we had to stop this same boy from brutally beating a smaller child who refused to steal food for him. He knew the difference between right and wrong, but he continued to use force and intimidation to manipulate others. Psychologists have observed a similar discord between beliefs and actions in less extreme settings [see "The Moral Development of Children," by William Damon; Scientific American, August 1999].

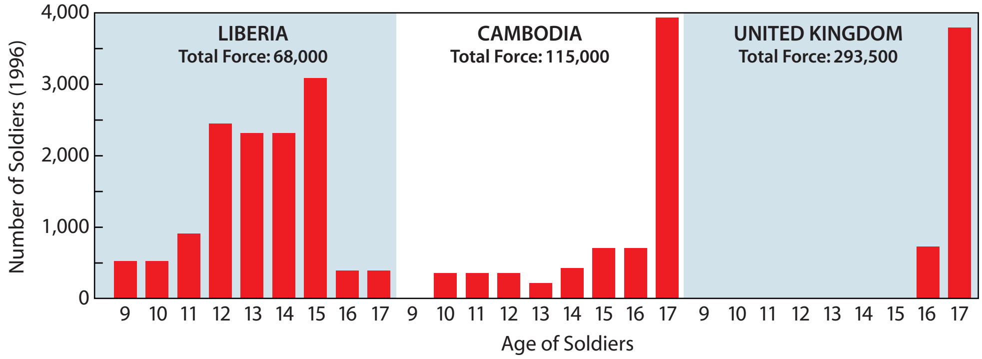
Will these children ever be able to rejoin society? No one yet knows. But our work in Mozambique suggests that unless aid workers reach out to them, they are very likely to be drawn to groups and ideologies that legitimize and reward their rage, fear and hateful cynicism. Gangs and militias will flourish well after the war officially ends.

First in War, Last in Peace

Any nation, society, ethnic group or political cause that uses children for military purposes clearly takes a totalistic approach to war that places no limits on the resources that can be marshaled to achieve its goals. This attitude is largely a modern phenomenon [*see box on preceding page*], and modern diplomacy and economic development will be needed to overcome it.

Several international treaties limit or prohibit the participation of minors in armed conflict. Both a 1977 amendment to the Geneva Conventions and the 1989 International Convention on the Rights of the Child (CRC) set the minimum age for combat soldiers at 15. All countries in the world have acceded to the CRC except the U.S. and Somalia. (The Clinton administration signed it in 1995, but conservative senators have held up ratification for reasons unrelated to child soldiers.) The U.S. used to oppose a proposed Optional Protocol that would raise the minimum age, but this past January, U.S. negotiators agreed to a minimum age of 18 as long as 17-year-olds could still be recruited. The protocol explicitly applies the same standards to all armed groups, not just the armed forces of a state. Human-rights advocates see it as a breakthrough in the universal recognition of children's rights.

In 1998 another breakthrough came when diplomats drafted the statute of the International Criminal Court. It lists the use of child soldiers—those younger than 15, as the CRC specifies—in its catalogue of war crimes. When the statute enters into force (after being ratified by 10 countries, as is expected in mid-2001), organizations such as ours (Save the Children) plan to lobby to encompass children up to the age of 18, following the Optional Protocol.



YOUNG CHILDREN make up a large fraction of armed groups in Liberia and other parts of Africa; the percentage is smaller in Cambodia and elsewhere in Asia and in Latin America. Several developed nations recruit 16-year-olds but are now raising the minimum age.

LAURIE GRACE; SOURCE: CASE STUDIES COMPILED BY SWEDISH SAVE THE CHILDREN

Of course, making laws is not the same as enforcing them. The African Charter on the Rights and Welfare of the Child sets the minimum age for recruitment at 18, yet Africa accounts for more than half the countries where children are fighting. Many countries violate their own national standards. In Burundi, for example, armed groups comprising 12- to 25-year-olds have been formed with the encouragement of the government. And rebel groups and irregular forces are even less constrained than governments are.

The problem is exacerbated by inconsistencies on the part of the international community. Although the Western response to ethnic cleansing in the Balkans was slow and often inept, in the end it sent an unambiguous message. In Bosnia, for example, the West branded the engineers of the ethnic cleansing as war criminals and got international warrants issued for their arrest. But no such efforts have been made in, say, Sierra Leone.

The behavior of states toward their youngest citizens simply does not enter into discussions of diplomatic recognition, membership of international organizations, or access to development and trading agreements. Leaders who exploit child soldiers, such as Liberia's Charles Taylor and the Congo's Laurent Kabila, are accepted as peers in the international community.

Among those of us working with these children, a focus of future research will be the role of aid groups in rebuilding civil societies. Humanitarian programs can be organized in a manner that promotes children's rights and other basic values. Ultimately, economic development will prove crucial. It is no coincidence that forced recruitment of children occurs most frequently in societies where the standard of living has stagnated or suddenly declined. And although the elimination of poverty may appear to be a naive and unattainable goal, we are not so pessimistic. Indeed, as the 1997 U.N. Human Development Report argues, "Eradicating absolute poverty in the first decade of the 21st century is … a moral imperative." SA

The Authors

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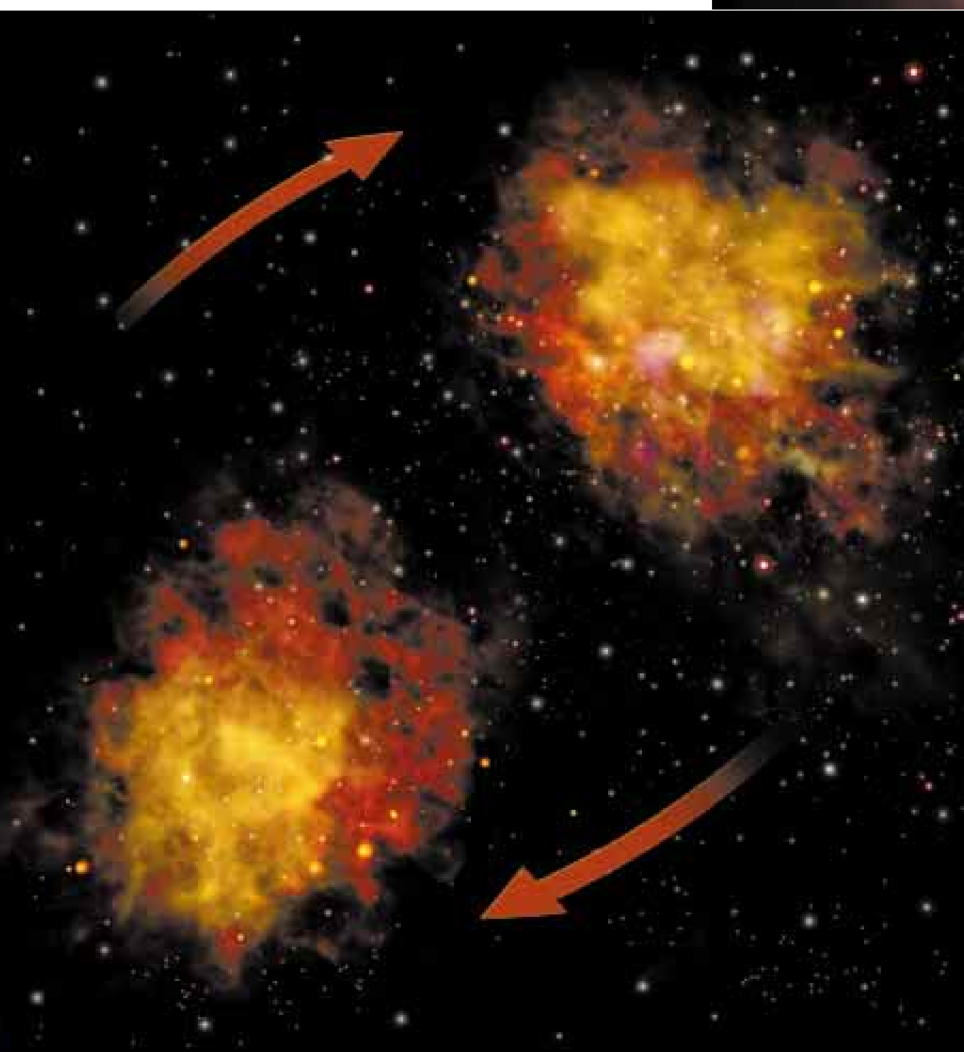
An annotated **bibliography on the psychological effects of war** is at www.qut.edu.au/publications/bsspsych_report/intro.html

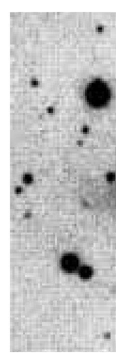
Information on child soldiers is available from UNICEF (www.unicef.org/graca), the Coalition to Stop the Use of Child Soldiers (www.child-soldiers.org), Swedish Save the Children (www.rb.se/chilwar) and Human Rights Watch (www.hrw.org/campaigns/crp).

Dwarf *Galaxies*

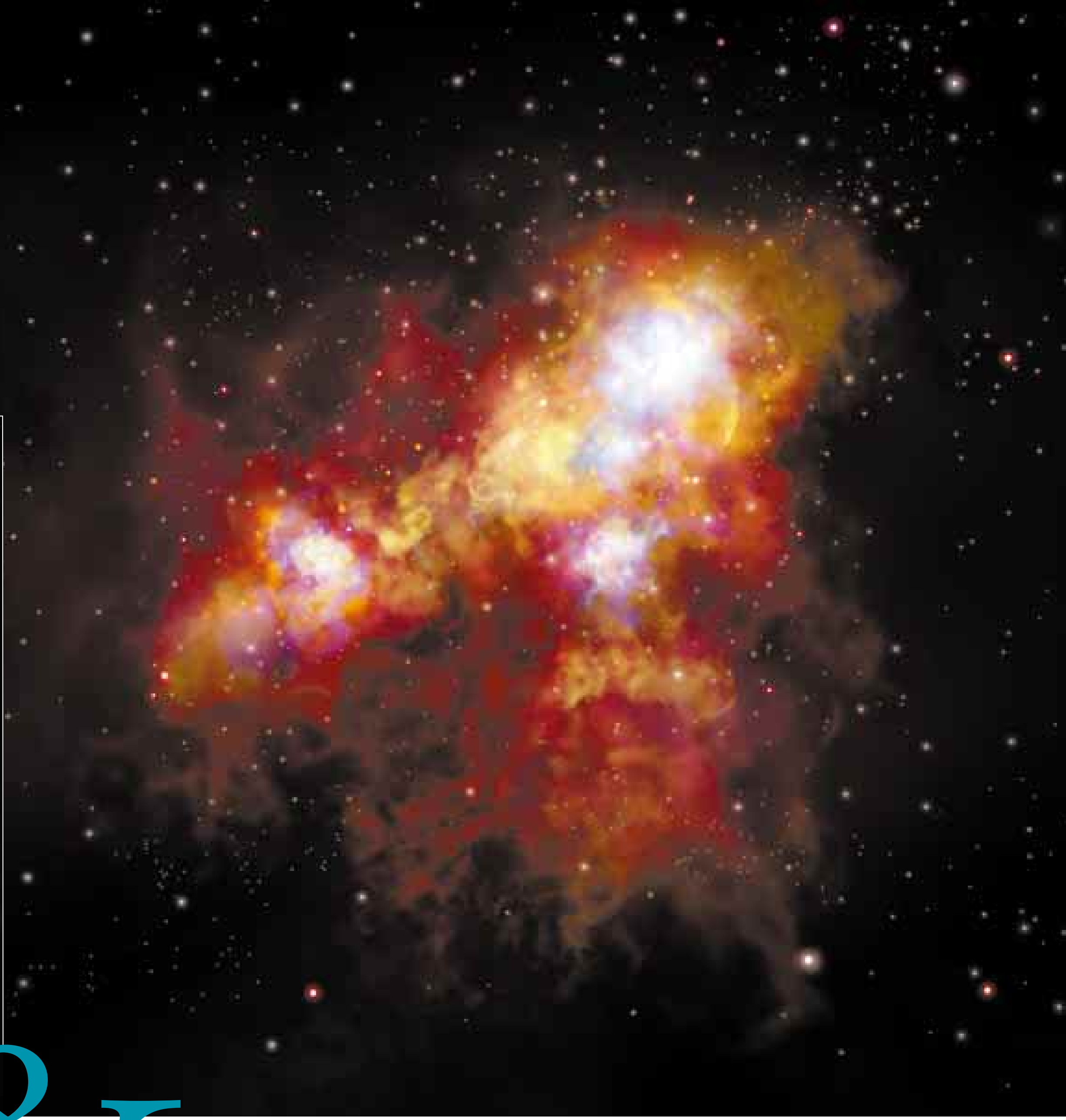
Diminutive galaxies occasionally experience spectacular bursts of star formation. These starbursts are giving astronomers a glimpse of the universe's early history

by Sara C. Beck

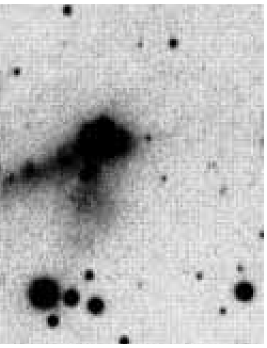




GALACTIC MERGER triggers star formation in this artist's conception of the evolution of dwarf starburst galaxy II Zw 40. In the first stage (*left*), two dwarf galaxies consisting of old red stars and clouds of atomic gas (*yellow*) are pulled by gravitational attraction into orbit around each other. As they spiral closer, tails of gas and stars are drawn out by tidal forces (*above*) and clumps of young blue stars begin to form. The final stage (*opposite page, top*) portrays the merged galaxy as it appears today in telescope images (*right*).



& Starbursts



About 12 million light-years from the earth is a large, beautiful barred spiral galaxy named M83. Pictures of this galaxy have appeared on many astronomy posters and book jackets. Looking closely at these images, one may notice, off to the side of M83, a small nebula of roughly elliptical shape. This is the dwarf galaxy NGC 5253. The casual viewer might think it is an insignificant companion to M83, but looks can be deceiving. That little galaxy is in the midst of an extreme starburst—it is forming stars at a fantastic pace. In proportion to its size, NGC 5253's star formation rate is many times higher than M83's.

In recent years, astronomers have discovered that dwarf galaxies such as NGC 5253 are far more common than previously supposed. Moreover, these galaxies are very different from their bigger cousins: they spend billions of years in a dormant state, then erupt in furious, short-lived bursts of star formation. Starbursts also occur in large galaxies, but the radiation from those

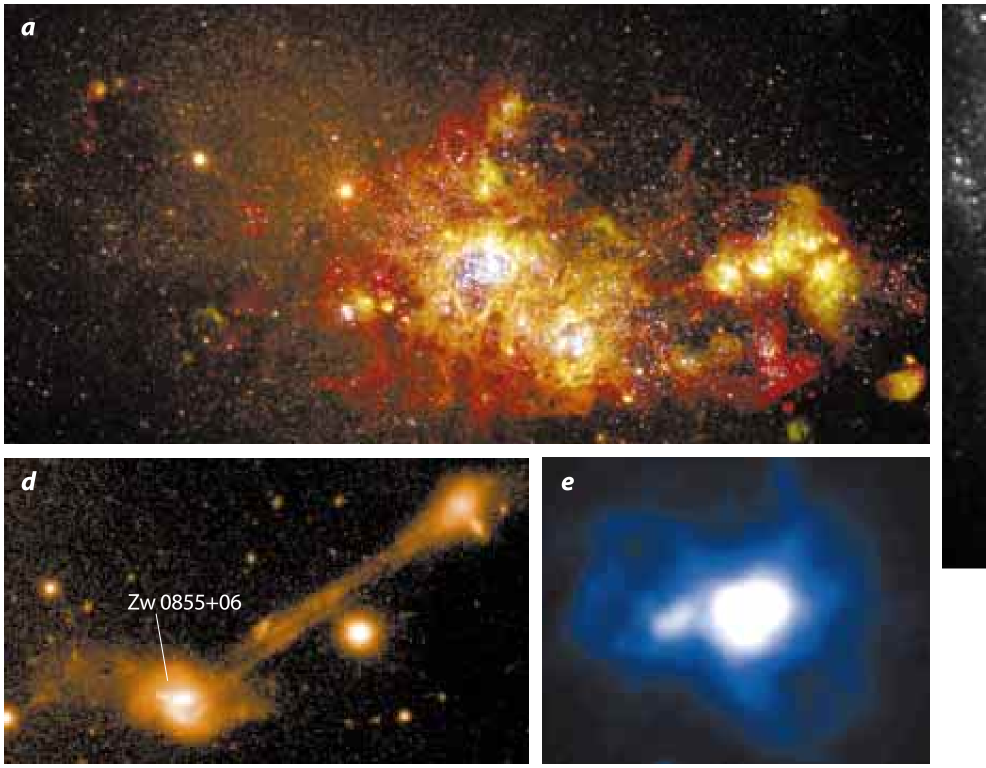
ALFRED T. KAMAJIAN; AURA/NOAO/NSF (*telescope image*) bursts is usually obscured by other galactic emissions; only in dwarf starburst galaxies can researchers get a clear look at this intriguing phenomenon. These galaxies also hold clues to the early history of the universe—they are relics of an ancient time, composed of material that has changed little since the big bang.

What causes starbursts in dwarf galaxies, and why are they so important to astronomers? To answer these questions, we must examine the mechanics of star formation. Astronomers know that stars have been forming for almost the entire duration of the universe. Our own galaxy, the unremarkable large spiral called the Milky Way, contains at least 100 billion stars. Star formation in the Milky Way is a slow, steady process involving the contraction of vast clouds of interstellar gas and dust. Every year, on average, about one solar-mass of gas and dust (that is, an amount with the mass of our sun) turns into new stars.

In contrast, a starburst is a relatively brief period—from one million to 20 million years—during which the rate of star formation is much higher than average. Astronomers have observed galaxies in which the rate is 100 times higher than the Milky Way's. We know this must be a short-lived stage because if it had been going on for more than a few hundred million years the galaxy would have run out of the gas from which stars are made.

The increased star formation rate causes a dramatic rise in the galaxy's brightness. Because starbursts are brief, they are dominated by the radiation from hot young stars of 20 solar-masses or more, which have lifetimes of only a few million years. These stars are tens of thousands of times brighter than the sun. They heat and ionize the dense clouds of gas and dust from which they form; the clouds absorb the stars' visible and ultraviolet light and then reradiate the energy as radio and infrared emissions. A strong starburst can be almost as bright as a quasar, the most luminous object in the universe. Because a starburst's luminosity is concentrated in the radio and infrared parts of the spectrum, the phenomenon has been recognized and studied only in the past 20 years as new telescopes and satellites have allowed scientists to observe these wavelengths.

Many astronomers believe that starbursts play a pivotal role in galactic evolution and in the creation of star clusters. For this reason, scientists are eager to know what triggers these sudden episodes, how they proceed and what turns them off. These questions may be easier to answer in dwarf galaxies, which hold 100 million or fewer stars, than in the large spirals such as the Milky Way and M83.



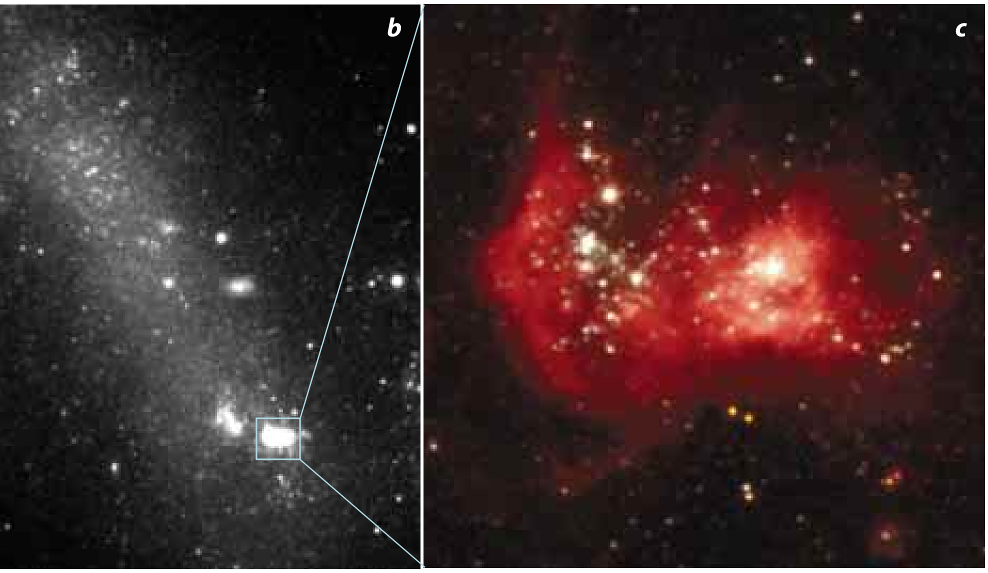
A Deluge of Dwarfs

Researchers have given serious attention to dwarf galaxies only in recent years simply because most of them are so faint. The two best-known dwarfs are the Large and Small Magellanic Clouds, which seem bright because they are relatively close to our galaxy (less than 300,000 light-years away). No other dwarf galaxies are visible to the naked eye. But powerful telescopes, modern detectors and large-scale surveys have found that dwarfs actually outnumber large galaxies by a wide margin. The Local Group, the cluster of galaxies that includes our own, contains (at last count) just two large spirals—the Milky Way and Andromeda—and about 40 dwarfs. This ratio is probably typical of most of the nearby universe.

Some dwarf galaxies are called dwarf ellipticals because of their shape, and the smallest and faintest of these are called dwarf spheroidal galaxies. But most dwarfs have no simple structure or shape and are thus called irregulars. Observers have often referred to them as "blobs," "little fuzzies" or "fried eggs," which gives an idea of their typical appearance, but in print the name "irregular" is preferred.

Dwarf galaxies are not scaled-down versions of large galaxies. Their evolution is driven by different mechanisms. Spiral galaxies have giant clouds of molecular hydrogen, helium and dust that can readily form stars. The spiral-arm pattern is maintained by density waves, which trigger star formation by compressing the molecular clouds that they pass through. As a result, spiral galaxies are never completely quiescent; they always have some newly born stars.

In contrast, dwarf galaxies have little molecular hydrogen. They do have a lot of atomic hydrogen—that is, hydrogen atoms floating freely rather than bound into two-atom molecules. In a typical dwarf galaxy the mass contained in clouds of atomic hydrogen is 10 times greater than the mass in stars. Because these clouds are not nearly as dense as clouds of molecular hydrogen, they are less likely to collapse gravitationally and produce stars. Furthermore, dwarf galaxies do not have density waves or other organized gas motions that can cause a cloud to collapse. So dwarfs spend the great majority of their time in a quiescent state: during this stage, all their stars are faint, red and old. Only the starburst dwarfs have the hot, bright blue stars that indicate recent star formation.



DWARF STARBURST GALAXIES such as NGC 4214 (*a*) contain clumps of young blue stars surrounded by clouds of glowing gas. Starburst clumps are also visible in dwarf galaxy NGC 2366 (*b*); a close-up image taken by the Hubble Space Telescope shows a dense cluster of massive stars embedded in a gas cloud (*c*). The starburst in dwarf galaxy Zw 0855+06 (*d*) was apparently caused by a close encounter with another dwarf galaxy, which also created the bridge of stars between them. Dwarf starburst Henize 2-10 (*e*) has a tidal tail of gas, leading astronomers to believe it swallowed a smaller galaxy. Henize 2-10 also has shells of gas expelled by massive young stars.

Evidence for long periods of quiescence in dwarf galaxies can be found in their chemical content. Star formation changes a galaxy's composition: when massive stars reach the end of their lives, they explode in violent supernovae, which enrich the surrounding galactic gas with the heavy elements formed by the star's thermonuclear reactions. If no stars are born, however, the galaxy will remain chemically unevolved. The history of a galaxy can be roughly judged by its abundance of metals, as astronomers call all elements besides hydrogen and helium (to the disgust of chemists). The lower the metal abundance, the less evolved the galaxy.

The metal abundances of dwarf galaxies generally range from 2 to 30 percent of that in the sun's neighborhood, with the peak of the distribution around 10 percent. Only a few very active starburst dwarfs have metal abundances comparable to a spiral galaxy's. The unevolved state of dwarf galaxies has raised the possibility of finding one that is truly primordial—unchanged since the big bang. The galaxies with the lowest metal abundances detected so far—two dwarfs called I Zw 18 and SBS 0335-052—do not appear to be primordial: they seem to have already gone through a few generations of star formation. Nevertheless, the search continues. In the meantime, cosmologists can study these galaxies for clues to how the first generations of stars were born.

Bursting with Stars

Dwarf galaxies undergoing a starburst episode have a unique appearance. They contain patches or clumps of hot, young blue stars within a larger, fainter envelope of cool, older red stars. The starburst dwarfs are remarkable for their brightness. During the starburst, a dwarf can be as bright as a large spiral, whereas a quiescent dwarf of the same size would be only 1 percent as luminous or even fainter. All this activity comes from a small area: the diameters of the starburst clumps usually range from a few hundred to 1,000 light-years. (The galaxies themselves are typically less than 6,000 light-years in diameter.) Each clump contains hundreds to tens of thousands of bright O- and B-type stars. A starburst dwarf may contain several clumps, and they are usually not in the center of the galaxy.

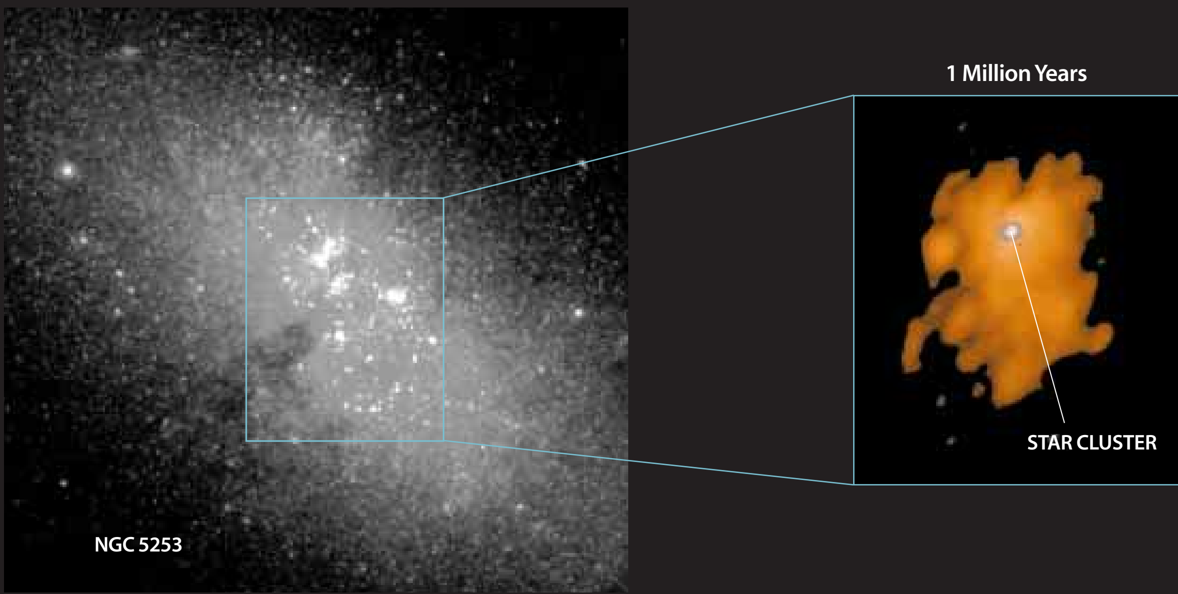
Unlike the Milky Way and other large galaxies, starburst dwarfs do not have a distribution of stars of all ages; they typically contain only the clumps of very young stars and the surrounding envelope of stars that are a few billion years older. Astronomers estimate the ages of stars in these galaxies by looking for specific stages of stellar evolution. Perhaps the most important age diagnostic for young stars is the Wolf-Rayet stage, which very massive stars (more than 25 solar-masses) achieve when they are between two million and 10 million years old. During this stage, stars expel most of their initial mass at speeds of a few thousand kilometers per second. The emission lines of ions in the rapidly moving material are broadened by the Doppler effect; instead of appearing as narrow stripes on the spectrum, they spread toward the red and blue ends. When astronomers see this broadening in the spectrum of a starburst clump, they know it contains a significant number of Wolf-Rayet stars and cannot be more than 10 million years old.

In large galaxies a starburst clump is often superimposed on the bright galactic nucleus or on one of the galaxy's spiral arms, making observations more difficult. What is more, the radiation caused by the continual star formation in the galaxy can be confused with the emissions from the starburst clump. This problem is particularly bad in the radio part of the spectrum. As noted earlier, the massive young stars in starburst clumps ionize the surrounding gas clouds. These clouds produce radio emissions with a thermal spectrum—the intensity of the emissions varies by frequency in a distinctive way. But when the massive stars go supernova, the remnants from the explosion emit radio waves in a nonthermal spectrum. The radio spectrum of a large galaxy is a combination of the thermal radiation from the current generation of massive stars and the nonthermal radiation from past generations. The nonthermal radiation, though, can be much stronger and last longer than the thermal radiation. Therefore, in a large galaxy the distinctive emissions from a starburst are often swamped by other emissions.

Dwarf galaxies, however, have no history of continual star formation, so the starburst clumps are much easier to observe in isolation. In the dwarf starburst galaxies NGC 5253 and II Zw 40, for example, only the thermal emissions from young stars are seen, because the radio contributions from earlier bursts of star formation have faded away. The absence of nonthermal emissions can be used as an age diagnostic: it means that none of the stars in the starburst clump have gone supernova yet, so the starburst's age must be less than the age at

NASA/SPACE TELESCOPE SCIENCE INSTITUTE (*NGC 4214 and NGC 2366 close-up*); CFHT (*NGC 2366*); DAVID I. MÉNDEZ AND CÉSAR ESTEBAN *Instituto de Astrofísica de Canarias (Zw 0855+06 and Henize 2-10)*

EVOLUTION OF A STARBURST



YOUNG STARBURST at the center of dwarf galaxy NGC 5253 (*above left*) was apparently triggered when the galaxy absorbed an intergalactic gas cloud. The youngest part of the starburst, which is probably less than one million years old, is visible only in radio and infrared images (*above right*) because its stars are still enshrouded by the nebula from which they formed. Astronomers believe that after 10 million years stellar winds will blow away the surrounding gas, as shown in the artist's rendering (*opposite page, left*), and that after several billion years the starburst clump will evolve into a globular cluster, perhaps resembling NGC 6093 in our own galaxy (*opposite page, right*).

which these massive stars explode (a few million years). This estimate agrees with other observations indicating that the starbursts in NGC 5253 and II Zw 40 are the youngest detected so far.

The youngest part of the starburst in NGC 5253 cannot be viewed optically, because it is still enshrouded by the cloud of gas and dust from which it formed. But a detailed study has shown that its radio and infrared emissions are concentrated in a very small source, which is believed to be a clump of 100,000 extremely young stars in a region only about three to six light-years in diameter. The stellar content and size of this source are highly similar to those of globular clusters, the dense, spherical clumps of stars seen in the Milky Way and other large galaxies.

The Milky Way's globular clusters, however, are at least several billion years old—they contain the oldest stars in the galaxy. The logical conclusion is that our galaxy has not formed globular clusters for many billions of years or that all newly formed clusters have been pulled apart and destroyed by gravitational stresses as they orbited through the galaxy's disk. The starbursts in NGC 5253 and other dwarf galaxies may well be globular clusters in formation. If so, they may reveal hidden aspects of our own galaxy's history.

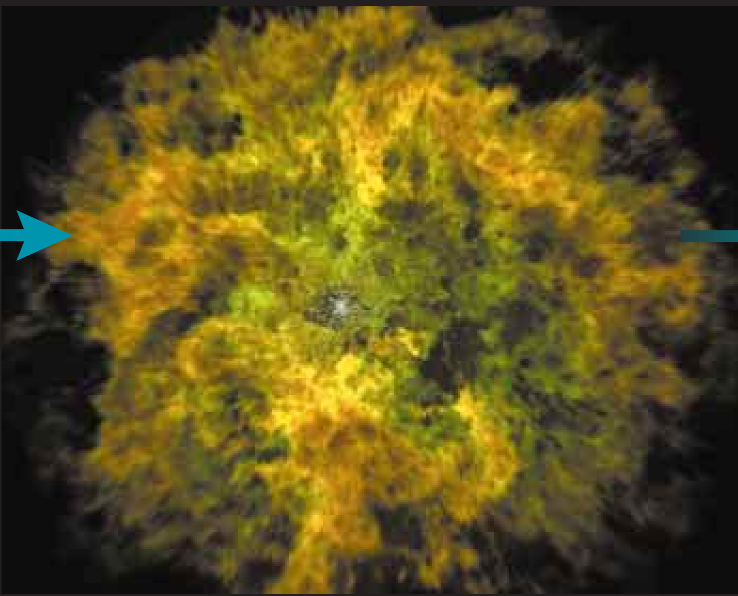
We must remember, though, that what is true for dwarf galaxies may not always be true for large galaxies. One important difference is in star propagation—how the birth of stars in one part of the galaxy can lead to the formation of stars in another part. The apparently random distribution of starburst clumps in dwarfs raises the question of how star formation can spread through a galaxy that has no spiral arms or other organized gas motions. The currently favored model is called Self-Propagating Stochastic Star Formation. In this model a starburst clump in one part of the galaxy triggers secondary starbursts in other parts. The massive young stars in the first center of activity disturb the gas in an adjacent region with stellar winds, ionization and other energetic activities. The gas then collapses and begins its own starburst. The process continues until there is not enough gas in position to be affected by the young stars. This model seems to suit the progress of star formation in dwarfs but is probably not applicable to spirals. And it leaves open the question of what caused the initial starburst.

How starbursts are triggered is an important question for large galaxies as well as dwarfs, and there are undoubtedly different answers for different galaxies. But the best-studied starburst dwarfs seem to be interacting with, merging into or absorbing other astronomical objects. For example, II Zw 40 is known as the "X marks the spot" galaxy because it appears to consist of two dwarf galaxies that are merging [*see illustration on pages 66 and 67*]. Or consider Henize 2-10, a relatively large dwarf galaxy with a relatively mature starburst (about 10 million years old). Astronomers believe that it probably gobbled up a much smaller galaxy perhaps 100 million years ago. The smaller galaxy has been well absorbed; only a tidal tail of gas stretching out of Henize 2-10 can still be seen [*see illustration on page 68*]. The starburst dwarf Zw 0855 +06 is interacting with another dwarf (with no starburst) that is close enough to cause tidal disturbances in the galaxy. And there are many other examples.

Dwarf Encounters

Close encounters also cause starbursts in large galaxies. Collisions and mergers of galaxies do not affect the existing stars—the stars in one galaxy almost never collide with the stars in another because there is so much space between stars in even the densest parts of galaxies. But the interactions can dramatically affect the galaxies' gas clouds, which experience shocks, compression and gravitational stresses that make them fragment, collapse and form stars. These processes

10 Million Years



Several Billion Years

should work just as well in dwarf galaxies as they do in larger systems.

Many of the dwarf starbursts, however, are not encountering other dwarf galaxies but systems smaller and fainter than themselves. If dwarf galaxies are the little fish in the celestial pond, what littler fish do they eat? Some astronomers believe that these small systems are clouds of atomic gas (mostly hydrogen) with masses ranging from one million to 10 million solar-masses. For example, NGC 5253 may have accreted a small gas cloud (roughly one million solar-masses) from intergalactic space. Researchers have conducted sensitive radio searches for intergalactic gas clouds with the characteristic emissions of atomic hydrogen. They have found that starburst dwarf galaxies are much more likely to have such gas clouds as companions than nonstarburst dwarfs are.

The hypothesis that starbursts in dwarf galaxies can be triggered by interactions with other dwarfs or intergalactic gas clouds may explain why bursts occur sporadically and at long intervals. But what turns the starburst off? The answer may be found in a striking feature of starburst dwarfs: many of them are surrounded by or contain large-scale structures of ionized gas, shaped like shells, bubbles, halos, forks or chimneys. These structures reflect the vigorous life of massive young stars, which generate strong outflows of gas. If they are massive enough, they may pass through the Wolf-Rayet phase and then die as supernovae. The shells and bubbles seen in starburst dwarfs are most likely the remnants of massed Wolf-Rayet winds and supernova explosions.

Violent mass loss typifies all massive young stars, not just those in dwarf galaxies, and ionized bubbles, plumes and filaments are seen in large starburst galaxies as well. But those structures in dwarf galaxies extend much farther from the galaxy than those in large systems do. The explanation is simply that the smaller mass and weaker gravity of a dwarf galaxy make it possible for the expelled gas to move farther from the galaxy and in many cases to escape it completely. Starbursts are apparently self-braking—the energetic stellar activity disrupts the interstellar gas on which star formation depends and brings the process to a halt. The less massive stars formed in the starburst, which do not become supernovae, blend in with the dwarf galaxy's underlying envelope of faint red stars. And the galaxy returns to its quiescent state: no longer a dwarf starburst but now an ordinary irregular dwarf, waiting for its next encounter.

Dwarf starburst galaxies are attracting more and more research interest as observational capabilities improve. Large optical and infrared telescopes in space and on the earth, radio and millimeter-wave arrays, and satellites that detect high-energy radiation have already made it possible for us to observe star formation in dwarf galaxies in unprecedented detail. By focusing on these dynamic systems, astronomers can study phenomena that cannot be seen anywhere else in the universe. Dwarf starbursts are clearly one of the best examples of good things found in small packages. SA

The Author

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Further Information

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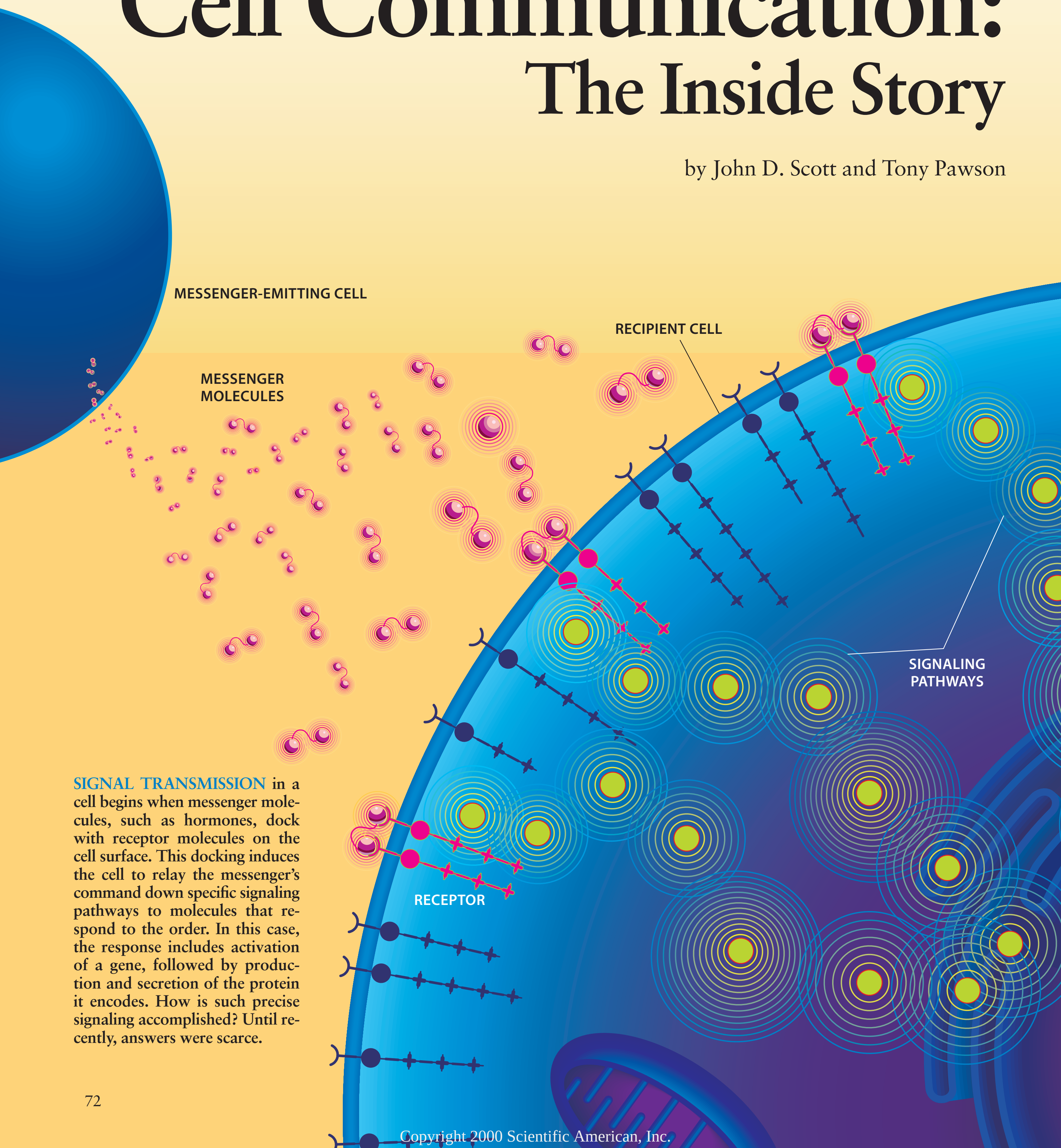
NASA/STScI (*galaxy and globular cluster images*); J. L. TURNER (*radio/infrared image*); ZAREH GORJIAN AND VAROUJAN GORJIAN NASA/Jet Propulsion Laboratory (*artist's rendering*)

The tiny cells in our bodies harbor amazing internal communication networks. Understanding how those circuits are organized could help scientists develop new therapies for many serious disorders

Cell Communication: The Inside Story

by John D. Scott and Tony Pawson



SIGNAL TRANSMISSION in a cell begins when messenger molecules, such as hormones, dock with receptor molecules on the cell surface. This docking induces the cell to relay the messenger's command down specific signaling pathways to molecules that respond to the order. In this case, the response includes activation of a gene, followed by production and secretion of the protein it encodes. How is such precise signaling accomplished? Until recently, answers were scarce.

As anyone familiar with the party game "telephone" knows, when people try to pass a message from one individual to another in a line, they usually garble the words beyond recognition. It might seem surprising, then, that mere molecules inside our cells constantly enact their own version of telephone without distorting the relayed information in the least.

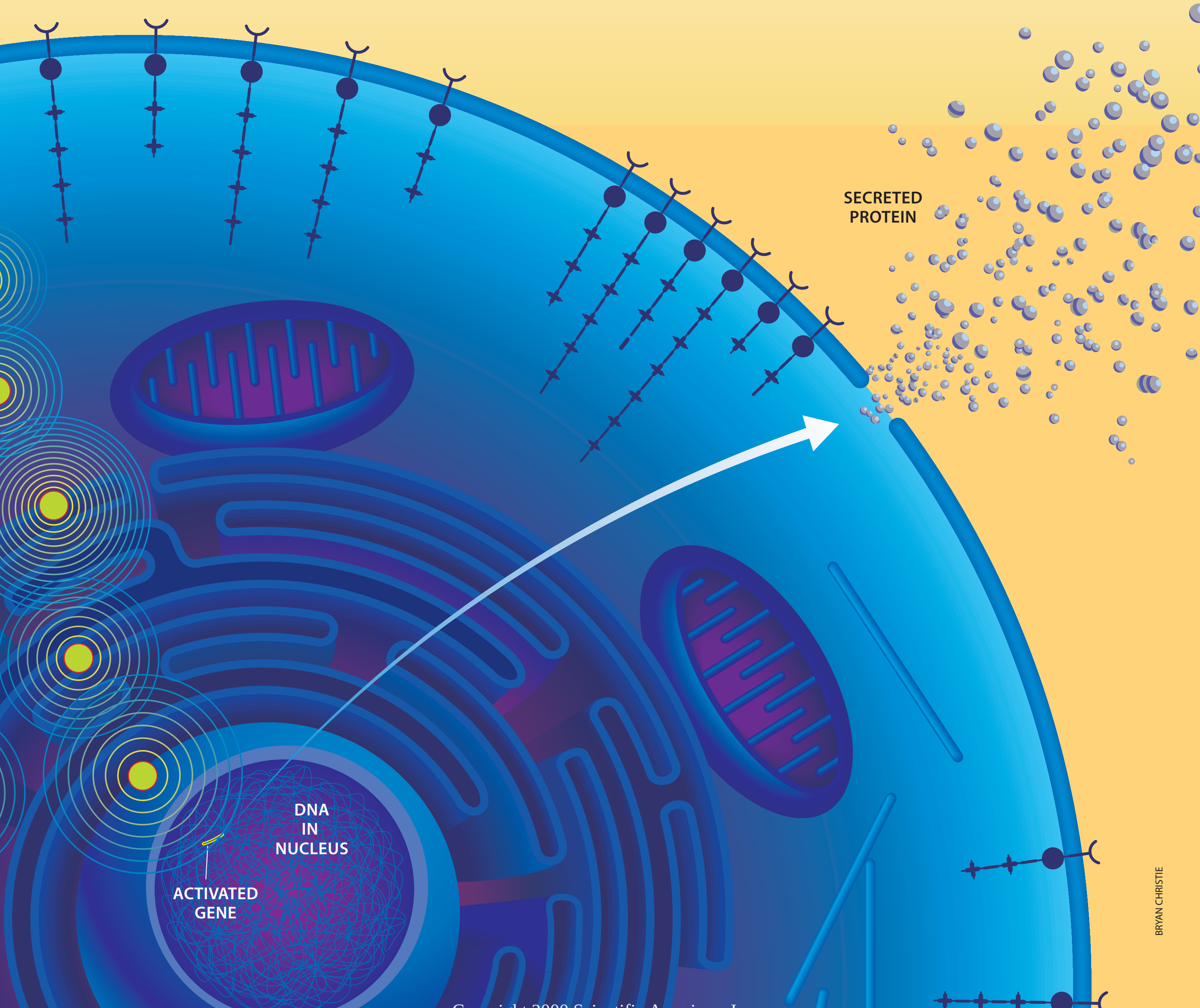
Actually, no one could survive without such precise signaling in cells. The body functions properly only because cells communicate with one another constantly. Pancreatic cells, for instance, release insulin to tell muscle cells to take up sugar from the blood for energy. Cells of the immune system instruct their cousins to attack invaders, and cells of the nervous system rapidly fire messages to and from the brain. Those messages elicit the right responses only because they are transmitted accurately far into a recipient cell and to the exact molecules able to carry out the directives.

But how do circuits within cells achieve this high-fidelity transmission? For a long time, biologists had only rudimentary explanations. In the past 15 years, though, they have made great progress in unlocking the code that cells use for their internal communications. The ongoing advances are suggesting radically new strategies for attacking diseases that are caused or exacerbated by faulty signaling in cells—among them cancer, diabetes and disorders of the immune system.

Refining the Question

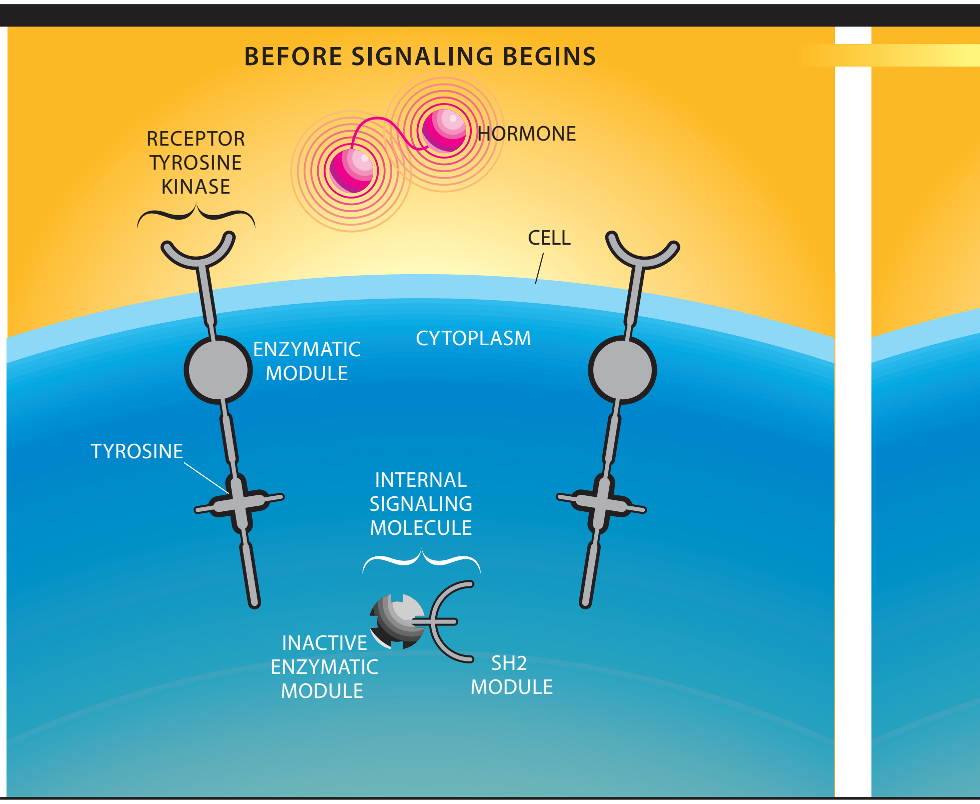
The earliest insights into information transfer in cells emerged in the late 1950s, when Edwin G. Krebs and Edmond H. Fischer of the University of Washington and the late Earl W. Sutherland, Jr., of Vanderbilt University identified the first known signal-relaying molecules in the cytoplasm (the material between the nucleus and a cell's outer membrane). All three received Nobel Prizes for their discoveries.

By the early 1980s researchers had gathered many details of how signal transmission occurs. For instance, it usually begins after a messenger responsible for carrying information



The Role of Modules in Signaling

The molecules that form signaling circuits in cells are often modular—built from components that carry out distinct tasks. This discovery emerged in part from studies of molecules known as receptor tyrosine kinases (*pogo-stick shape in first panel*). When a hormone docks with those molecules at the surface of a cell (*second panel*), the receptors pair up and add phosphates to tyrosine, an amino acid, on each other's cytoplasmic tails. Then so-called SH2 modules in certain proteins hook onto the altered tyrosines (*last panel*). This linkage enables "talkative," enzymatic modules in the proteins to pick up the messenger's order and pass it along.



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between cells (often a hormone) docks temporarily, in lock-and-key fashion, with a specific receptor on a recipient cell. Such receptors, the functional equivalent of antennae, are able to relay a messenger's command into a cell because they are physically connected to the cytoplasm. The typical receptor is a protein, a folded chain of amino acids. It includes at least three domains: an external docking region for a hormone or other messenger, a component that spans the cell's outer membrane, and a "tail" that extends a distance into the cytoplasm. When a messenger binds to the external site, this linkage induces a change in the shape of the cytoplasmic tail, thereby facilitating the tail's interaction with one or more information-relaying molecules in the cytoplasm. These interactions in turn initiate cascades of further intracellular signaling.

Yet no one had a good explaination for how communiqués reached their destinations without being diverted along the way. At that time, cells were viewed as balloonlike bags filled with a soupy cytoplasm containing floating proteins and organelles (membrane-bound compartments, such as the nucleus and mitochondria). It was hard to see how, in such an unstructured milieu, any given internal messenger molecule could consistently and quickly find exactly the right tag team needed to convey a directive to the laborers deep within the cell that could execute the order.

On the Importance of Lego Blocks

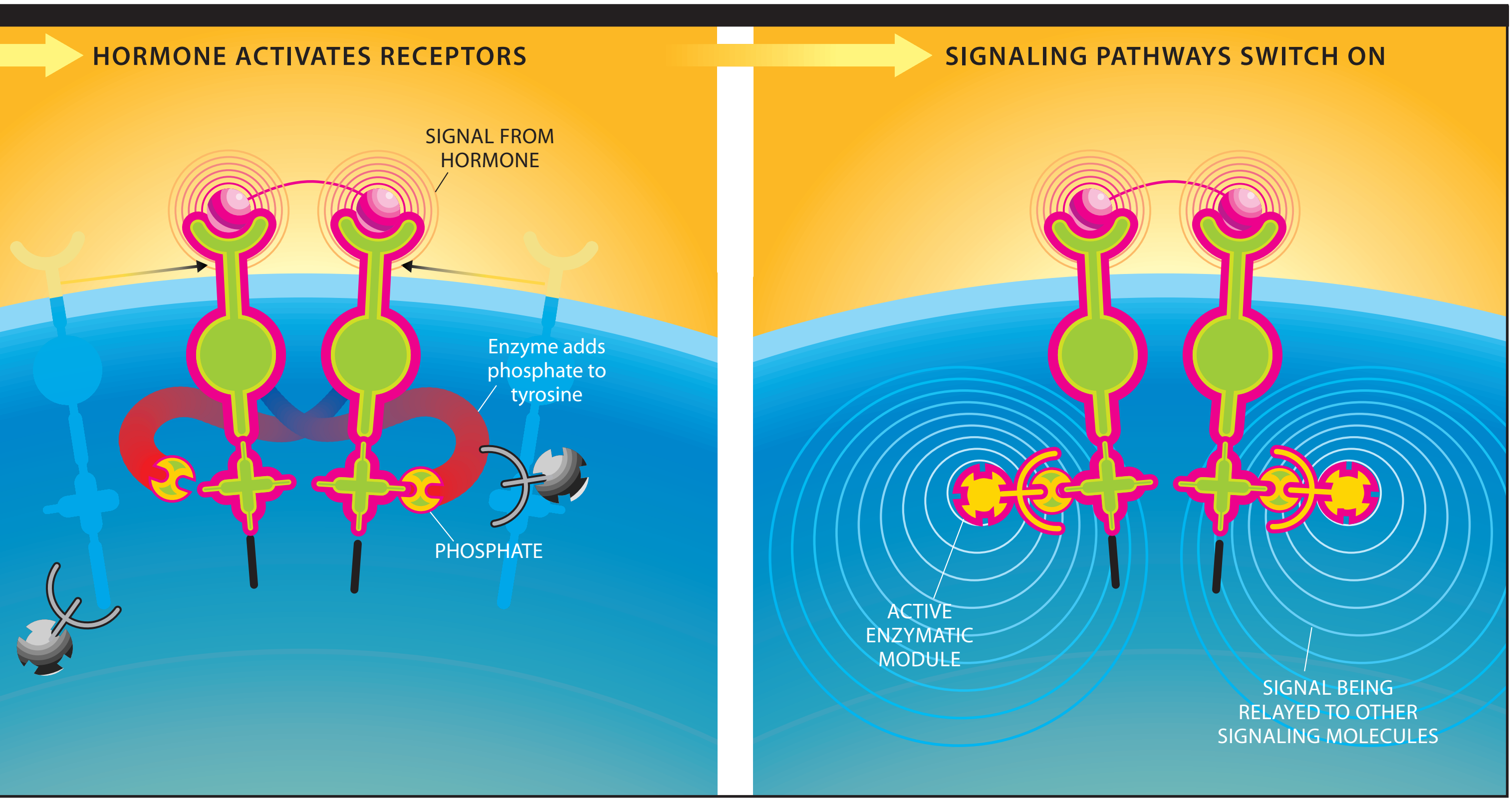
Today's fuller understanding grew in part from efforts to identify the first cytoplasmic proteins that are contacted by activated (messenger-bound) receptors in a large and important family: the receptor tyrosine kinases. These vital receptors transmit the commands of many hormones that regulate cellular replication, specialization or metabolism. They are so named because they are kinases—enzymes that add phosphate groups to ("phosphorylate") selected amino acids in a protein chain. And, as Tony R. Hunter of the Salk Institute for Biological Studies in La Jolla, Calif., demonstrated, they specifically put phosphates onto the amino acid tyrosine.

In the 1980s work by Joseph Schlessinger of New York University and others indicated that the binding of hormones to receptor tyrosine kinases at the cell surface causes the individual receptor molecules to cluster into pairs and to attach phosphates to the tyrosines on each other's cytoplasmic tails. In trying to figure out what happens next, one of us (Pawson) and his colleagues found that the altered receptors interact directly with proteins that contain a module they called an SH2 domain. The term "domain" or "module" refers to a relatively short sequence of about 100 amino acids that adopts a defined three-dimensional structure within a protein.

At the time, prevailing wisdom held that messages were transmitted within cells primarily through enzymatic reactions, in which one molecule alters a second without tightly binding to it and without itself being altered. Surprisingly, though, the phosphorylated receptors did not necessarily alter the chemistry of the SH2-containing proteins. Instead many simply induced the SH2 domains to latch onto the phosphate-decorated tyrosines, as if the SH2 domains and the tyrosines were Lego blocks being snapped together.

By the mid-1990s groups led by Pawson, Hidesaburo Hanafusa of the Rockefeller University and others had revealed that many of the proteins involved in internal communications consist of strings of modules, some of which serve primarily to connect one protein to another. At times, whole proteins in signaling pathways contain nothing but linker modules.

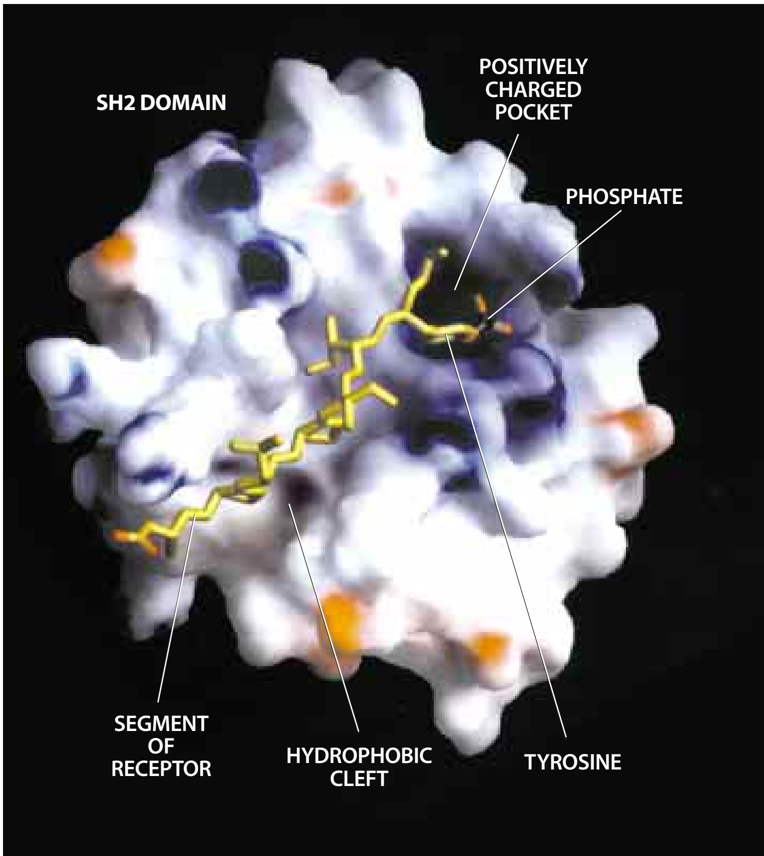
But how did those nonenzymatic modules contribute to swift and specific communication in cells? One answer is that



they help enzymatic domains transmit information efficiently. When a protein that bears a linker also includes an enzymatic module, attachment of the linker region to another protein can position the enzymatic module where it most needs to be. For example, the act of binding can simultaneously bring the enzymatic region close to factors that switch it on and into immediate contact with the enzyme's intended target. In the case of certain SH2-containing proteins, the linker module may originally be folded around the enzymatic domain in a way that blocks the enzyme's activity. When the SH2 domain unfurls to engage an activated receptor, the move liberates the enzyme to work on its target.

Even when a full protein is formed from nothing but protein-binding modules, it can function as an indispensable adapter, akin to a power strip plugged into a single socket. One module in the adapter plugs into a developing signaling complex, and the other modules allow still more proteins to join the network. An important benefit of these molecular adapters is that they enable cells to make use of enzymes that otherwise might not fit into a particular signaling circuit.

Nonenzymatic modules can support communication in other ways, too. Certain molecules in signaling pathways feature a protein-binding module and a DNA-binding module that meshes with, or "recognizes," a specific sequence of DNA nucleotides in a gene. (Nucleotides are the building blocks of genes, which specify the amino acid sequences of proteins.) James E. Darnell, Jr., of Rockefeller showed that when one of these proteins attaches, through its linker module, to an activated receptor kinase, the interaction spurs the bound protein to detach, move to the nucleus and bind to a

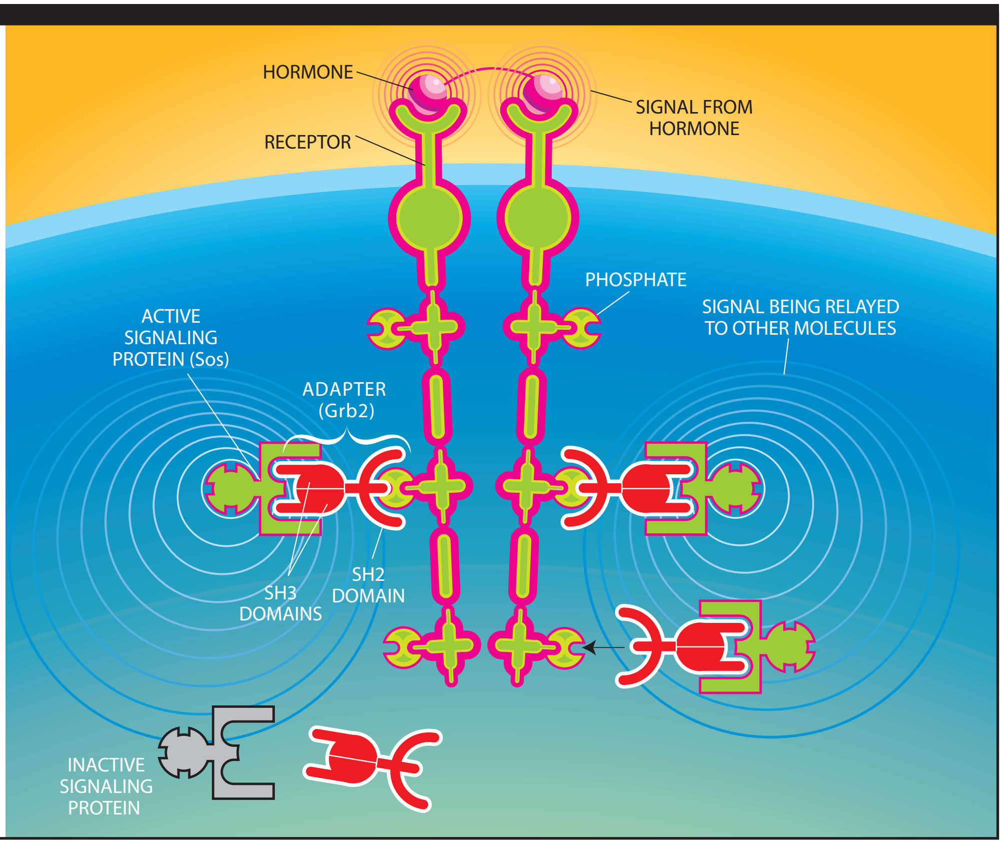


SH2 DOMAIN (*globular structure*) **in a signaling molecule is bound to a segment of a receptor** (*stick model*)**. The two fit together in part because a positively charged pocket in SH2 is attracted to a negatively charged phosphate that has been added to the amino acid tyrosine in the receptor. Also, the nearby amino acids in the receptor fit snugly into a hydrophobic (water-hating) groove on SH2. All SH2 domains can bind to phosphate-bearing tyrosines, but they differ in their binding partners because they vary in their ability to lock onto the amino acids that lie next to tyrosine in a protein.**

JULIE FORMAN-KAY *University of Toronto* AND TONY PAWSON

The Advantages of Adapters

Adapter molecules, which consist entirely of linker modules such as SH2 and SH3, turn out to be important players in many signaling pathways. They enable cells to make use of proteins that would otherwise be unable to hook into a given communication circuit. Here, for instance, the adapter protein Grb2 (*red*) draws an enzymatic protein—Sos—into a pathway headed by a receptor that itself has no means of interlocking with Sos.



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particular gene, thus inducing the synthesis of a protein. In this instance, the only enzyme in the signaling chain is the receptor itself; everything that happens after the receptor becomes activated occurs through proteins' recognition of other proteins or DNA.

As these various discoveries were being made, work in other areas demonstrated that the cytoplasm is not really amorphous after all. It is packed densely with organelles and proteins. Together such findings indicate that high-fidelity signaling within cells depends profoundly on the Lego-like interlocking of selected proteins through dedicated linker modules and adapter proteins. These complexes assure that enzymes or DNA-binding modules and their targets are brought together promptly and in the correct sequence as soon as a receptor at the cell surface is activated.

Fail-Safe Features Aid Specificity

Studies of receptor tyrosine kinases and of SH2 domains have also helped clarify how cells guarantee that only the right proteins combine to form any chosen signaling pathway. Soon after SH2 domains were identified, investigators realized that these modules are present in well over 100 separate proteins. What prevented different activated receptors from attracting the same SH2-containing proteins and thereby producing identical effects in cells? For the body to operate properly, it is crucial that diverse hormones and receptors produce distinct effects on cells. To achieve such specificity, receptors must engage somewhat different communication pathways.

The answer turns out to be quite simple. Every SH2 domain includes a region that fits snugly over a phosphate-bearing tyrosine (a phosphotyrosine). But each also includes a second region, which differs from one SH2 domain to another. That second region—as Lewis C. Cantley of Harvard University revealed—recognizes a particular sequence of three or so amino acids next to the phosphotyrosine. Hence, all SH2 domains can bind to phosphorylated tyrosine, but these modules vary in their preference for the adjacent amino acids in a receptor. The amino acids around the tyrosine thereby serve as a code to specify which version of the SH2 domain can attach to a given phosphotyrosine-bearing receptor. Because each SH2 domain is itself attached to a different enzymatic domain or linker module, this code also dictates which pathways will be activated downstream of the receptor. Other kinds of linker modules operate analogously.

A pathway activated by a protein called platelet-derived growth factor illustrates the principles we have described. This factor is often released after a blood vessel is injured. Its attachment to a unique receptor tyrosine kinase on a smooth muscle cell in the blood vessel wall causes such receptors to cluster and become phosphorylated on tyrosine. This change draws to the receptor a protein called Grb2, which consists of a specific SH2 domain flanked on either side by another linker domain, SH3. Grb2 is a classic adapter; it has no enzymatic power at all, but its SH3 domains (which like to bind to the amino acid proline) hook an enzyme-containing protein called Sos to the receptor. There Sos activates a membrane-associated protein known as Ras, which triggers a series of enzymatic events. These reactions ultimately stimulate proteins in the nucleus to activate genes that cause the cells to divide, an action that promotes wound healing.

The signaling networks headed by receptor tyrosine kinases seem to rely on relatively small adapter proteins. Analyses of communication circuits in nerve cells (neurons) of the brain show that some proteins in neuronal pathways have an incredibly large number of linker domains. These proteins are often called scaffolding molecules, as they permanently hold groups of signaling proteins together in one place. The existence of such scaffolds means that certain signaling networks are hardwired into cells. That hardwiring can enhance the speed and accuracy of information transfer.

Scaffolds Abound

One well-studied scaffolding protein goes by the name PSD-95. It operates primarily in neurons involved in learning. In nerve tissue, signals pass from one neuron to another at contact points called synapses. The first neuron releases a chemical messenger—a neurotransmitter—into a narrow cleft between the cells. Receptors on the second cell grab the neurotransmitter and then cause ion channels in the membrane to open. This influx of ions activates enzymes that are needed to propagate an electrical impulse. Once generated, the impulse travels down the axon, a long projection, to the axon's abundant tiny branches, inducing them to release more neurotransmitter. For the impulse to be produced, many components of the signaling system must jump into action virtually simultaneously.

Among the multiple linker modules in PSD-95 are three so-called PDZ domains. One binds to the cytoplasmic tail of the receptor for the neurotransmitter glutamate. A second grabs onto a membrane-spanning ion channel (which controls the inflow of potassium), and a third clasps proteins in the cytoplasm (as does an additional module in the scaffold). PSD-95 thus yokes together several signaling components at once, enabling them to coordinate their activities. The eye of a fruit fly also relies on a PDZ-containing scaffolding protein—InaD—for the efficient relay of visual information from the eye to the brain [*see illustration on next page*].

Yet another preformed signaling complex has been found

Getting a Line on Human Diseases

A surprising number of human disorders involve aberrant signaling in cells. Cancer, marked by uncontrolled cell proliferation and migration, is a prime example. At its root, cancer results from genetic mutations. Certain of those mutations work their mischief by leading to the overactivity of proteins in signal-relaying pathways within cells—notably, in pathways that normally induce the cells to divide in response to external commands. The affected proteins cause cells to behave as if other cells were constantly telling them to reproduce even when no such orders were sent.

Signal blockers are already in use against breast cancer, and more are under development. For instance, recent clinical trials suggest that a drug able to halt excessive "talk" by an enzyme called Abelson tyrosine kinase might help treat particular forms of leukemia.

Overzealous signaling is similarly destructive in an inherited syndrome known as X-linked lymphoproliferative (XLP) disease. In XLP patients, the normally benign Epstein-Barr virus sparks a deadly runaway response by "killer" T cells of the immune system.

Two years ago investigators found the reason for that lethal overreaction. People with XLP turn out to be missing a small protein termed SAP, which consists of a single SH2 domain (related to the SH2 domains mentioned in the main article). When killer T cells detect that other cells have become infected by the Epstein-Barr virus, they switch on an internal signaling cascade that enables them to attack the infected ones. Usually SAP keeps the attack under control—by sheathing interactive sites on some of the signaling components and thus breaking the signaling chain. But without SAP, XLP patients lack an important inhibitor of T cell hyperactivity.

"BLACK DEATH" epidemic of the 14th century was caused by *Yersinia pestis*. That bacterium makes use of signaling pathways in host cells to promote its own spread.

BETTMANN/CORBIS

Disease can also arise when intracellular signaling systems that should be busy are too quiet, as happens in various disorders involving inadequate immune responses. Insufficient signaling occurs as well in type 2 (maturity-onset) diabetes. Muscle and fat cells of the body take up sugar from the blood only after being told to do so by insulin sent from the pancreas. If insulin receptors on those cells fail to deliver insulin's message to relay molecules inside, diabetes (abnormally high blood sugar levels) can result. Oral medications designed to increase the activity either of the insulin receptor or of later players in the signaling cascade could potentially replace therapeutic insulin injections for some diabetics. One such compound, which stimulates the insulin receptor, has been tested successfully in mice.

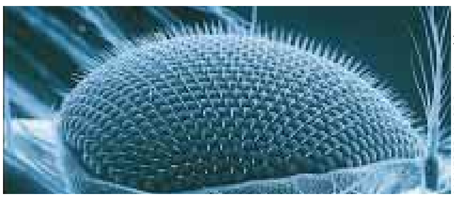
Bacteria and viruses are experts at exploiting the signaling systems of human cells to spread and reproduce. This capacity is especially evident in such bacteria as *Yersinia pestis,* which caused the "black death" plague of the 14th century, and in disease-causing strains of *Escherichia coli.* The microbes inject their own proteins into human cells. Some of these proteins alter signaling pathways in ways that can both promote the association of the bacteria with a host's cells and disarm the cells' antibacterial defenses.

Viruses, for their part, often gain entry into human cells by attaching to receptors that head signaling circuits; then they may modify a cell's internal communication networks to enhance their own replication and release. The human immunodeficiency virus (HIV), the cause of AIDS, is one of many viruses that act in these nefarious ways.

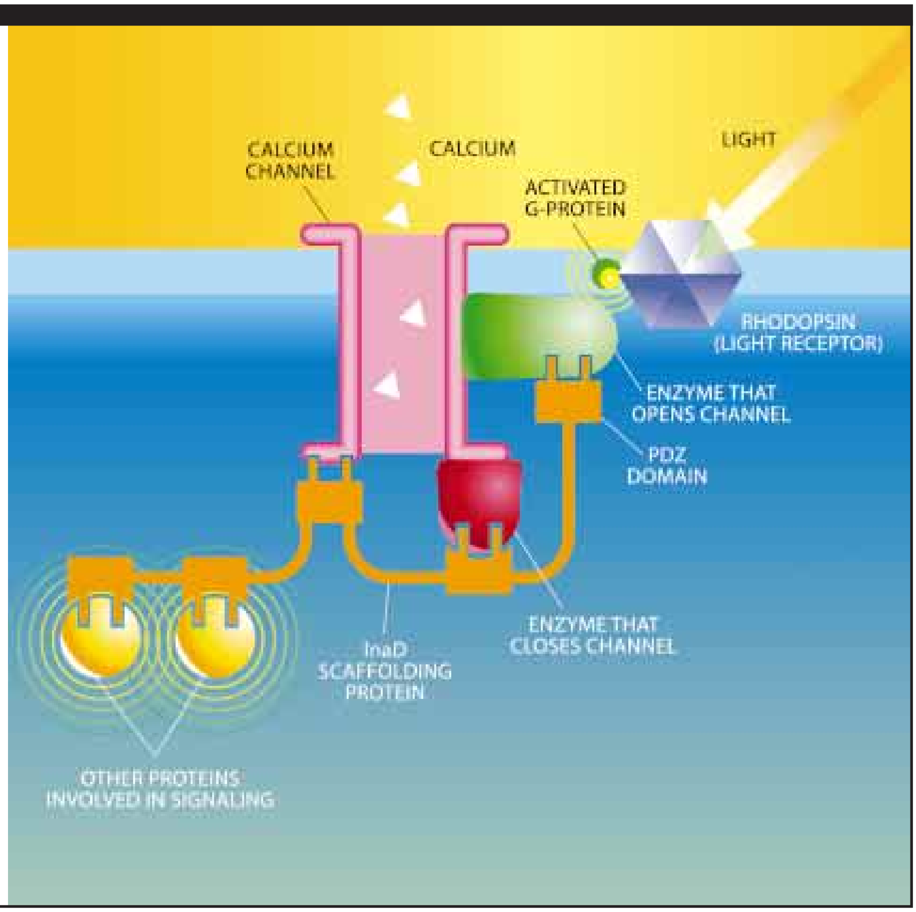
As the links between signaling abnormalities and disease become clearer, therapies that repair or compensate for those disruptions should become increasingly commonplace. —*T.P. and J.D.S.*

Scaffolds Speed Signal Transmission

Scaffolding proteins, which hold onto several other proteins, can ensure that multiple signaling molecules act almost simultaneously. One, InaD (*diagram*), operates in cells of the fruit-fly eye—a compound structure containing many smaller eyes (*photograph*)—and participates in sending visual messages to the brain. Three of the scaffold's five "PDZ" linker domains separately grasp an ion channel, an enzyme that opens the channel when light hits a nearby light receptor (rhodopsin) and an enzyme that closes the channel promptly thereafter. Two more PDZ domains help to relay information by holding other signaling molecules in place.



MANFRED KAGE *Peter Arnold, Inc.*



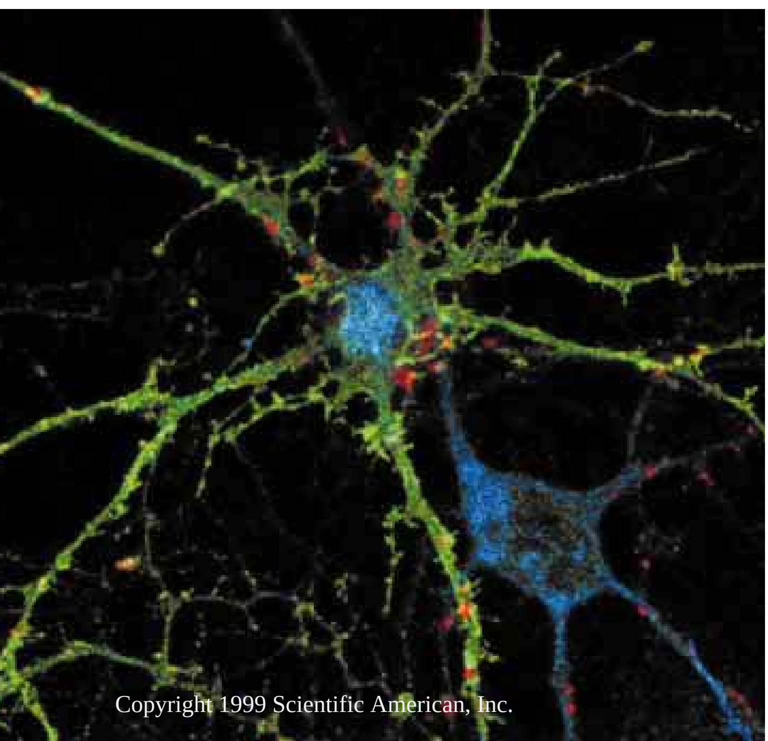
BRYAN CHRISTIE (*illustration*)

only recently, in mammalian neurons. The core is a scaffolding protein named yotiao. As one of us (Scott) and his colleagues have shown, this molecule grasps a dual-purpose, membrane-spanning protein that is both a glutamate receptor and an ion channel. It also clasps a kinase that adds phosphate to, and thereby opens, the ion channel when the receptor is activated by glutamate. And it anchors a phosphatase, an enzyme that removes phosphates from proteins. The bound phosphatase closes the ion channel whenever glutamate is absent from the receptor. This elegant arrangement ensures that ions flow through the channel only when glutamate is docked with the receptor.

Kinases and phosphatases control most activities in cells. If one kinase activates a protein, some phosphatase will be charged with inactivating that protein, or vice versa. Yet human cells manufacture hundreds of different kinases and phosphatases. Scaffolding proteins, it appears, are a common strategy for preventing the wrong kinases and phosphatases from acting on a target; they facilitate the proper reactions by holding selected kinases and phosphatases near the precise proteins they are supposed to regulate.

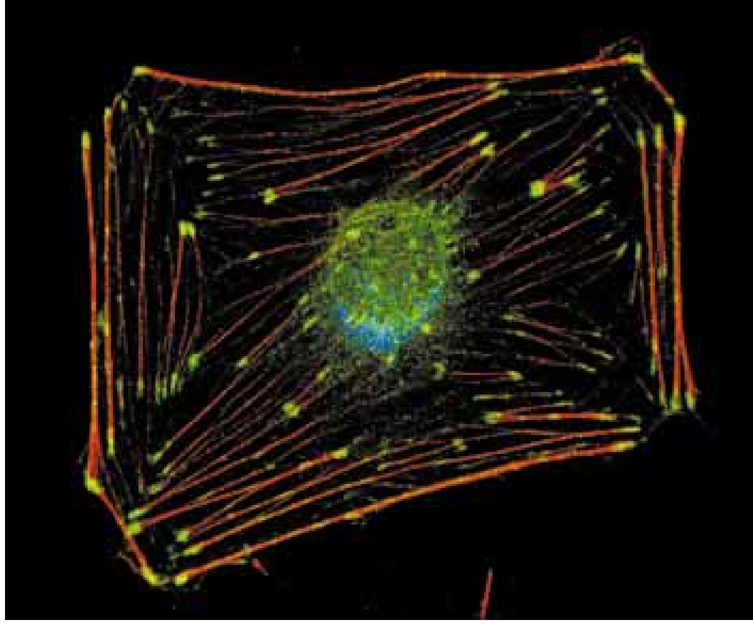
Many Payoffs

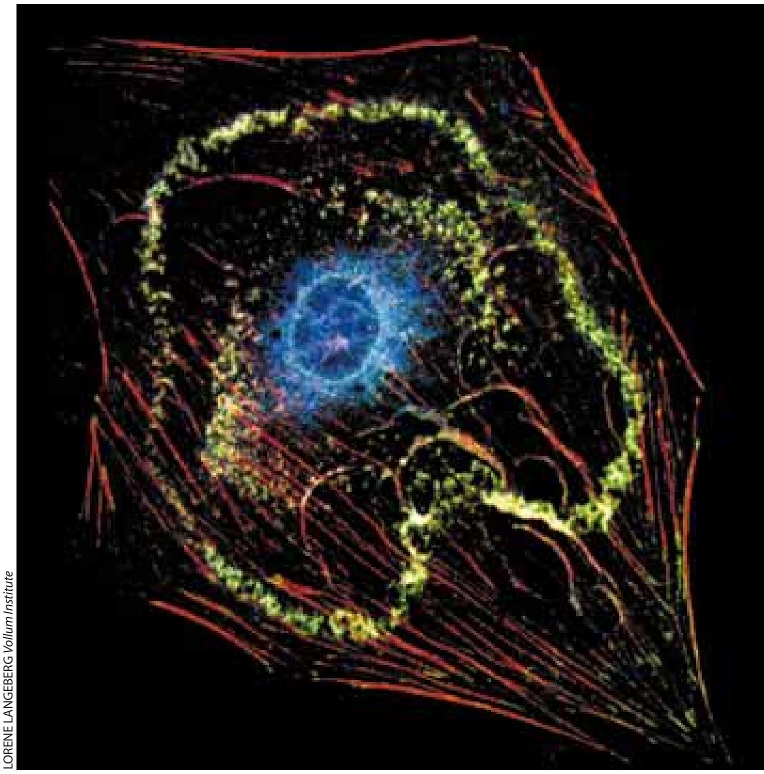
From an evolutionary perspective, the advent of a modular signaling system would be very useful to cells. By mixing and matching existing modules, a cell can generate many molecules and combinations of molecules and can build an array of interconnected pathways without having to invent a huge repertoire of building blocks. What is more, when a new module does arise, its combination with existing modules can in-



TWO SCAFFOLDING PROTEINS are highlighted in the larger nerve cell (neuron) in this micrograph. One, yotiao (*green*), tethers signal-relaying enzymes next to an ion channel involved in signal transmission. The other, PSD-95 (*red*), clusters a receptor and a different ion channel at selected synapses, the contact points between neurons. The blue in both neurons marks the location of a specific signaling enzyme.

LORENE LANGEBERG *Vollum Institute (micrograph)*





FLOW OF MESSAGE in a skin cell was made visible by coloring two components of a signaling pathway: a scaffolding protein (*green*) and one of two enzymes tethered to that scaffold (*blue*). Actin, a structured element in cells, is red. The top cell is quiet. Soon after an external messenger activated a signaling pathway in the bottom cell, the scaffolding protein moved its bound enzymes to their targets deeper in the cell. That movement is revealed by the yellow hue, which derives from the overlap of the colored signaling components with actin (to which the enzymes' targets were bound). The blue mass at the center reflects extra copies of the colored enzyme.

LORENE LANGEBERG *Vollum Institute*

crease versatility tremendously—just as adding a new area code to a city turns already assigned phone numbers into entirely new ones for added customers.

For cell biologists, merely chipping away at the mystery of how cells carry out their myriad tasks is often reward enough for their efforts. But the new findings have a significance far beyond intellectual satisfaction.

The much publicized Human Genome Project will soon reveal the nucleotide sequence of every gene in the human body. To translate that information into improved understanding of human diseases, those of us who study the functioning of cells will have to discern the biological roles of any newly discovered genes. That is, we will need to find out what the corresponding proteins do and what happens when they are overproduced, underproduced or made incorrectly.

We already know the amino acid sequences and the functions of many modules in signaling proteins. Hence, we have something of a key for determining whether the nucleotide sequence of a previously unknown gene codes for a signaling protein and, if it does, which molecules the protein interacts with. When we have enough of those interactions plotted, we may be able to draw a wiring diagram of every cell type in the body. Even with only a partial diagram, we may uncover ways to "rewire" cells when something goes wrong—halting aberrant signals or rerouting them to targets of our own choosing [*see box on page 77*]. We might, for instance, funnel proliferative commands in cancer cells into pathways that instruct the cells to kill themselves instead of dividing.

By learning the language that cells use to speak to one another and to their internal "workers," we will be able to listen in on their conversations and, ideally, find ways to intervene when the communications go awry and cause disease. We may yet reduce "body language" to a precise science. SA

The Authors

JOHN D. SCOTT and TONY PAWSON collaborate on understanding the molecular architecture that enables hormonal and other signals to be relayed properly within cells. Scott is an associate investigator at the Howard Hughes Medical Institute and a senior scientist at the Vollum Institute at the Oregon Health Sciences University. Pawson is head of the program in molecular biology and cancer at the Samuel Lunenfeld Research Institute of Mount Sinai Hospital in Toronto, a professor of molecular and medical genetics at the University of Toronto, and a distinguished professor of the Medical Research Council of Canada.

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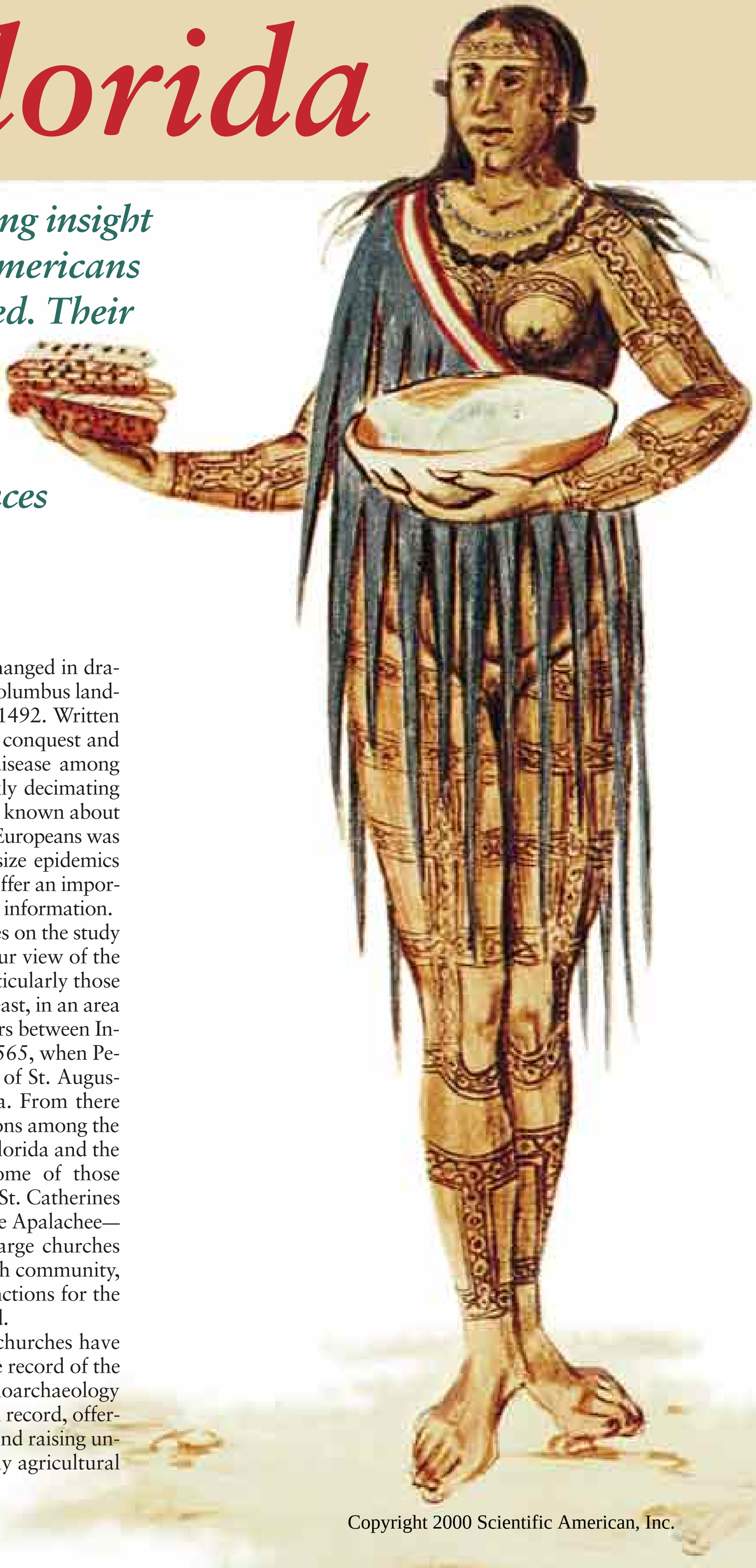
Reading the Bones of *La Florida*



New approaches are offering insight into the lives of Native Americans after the Europeans arrived. Their health declined not only because of disease but because of their altered diet and living circumstances

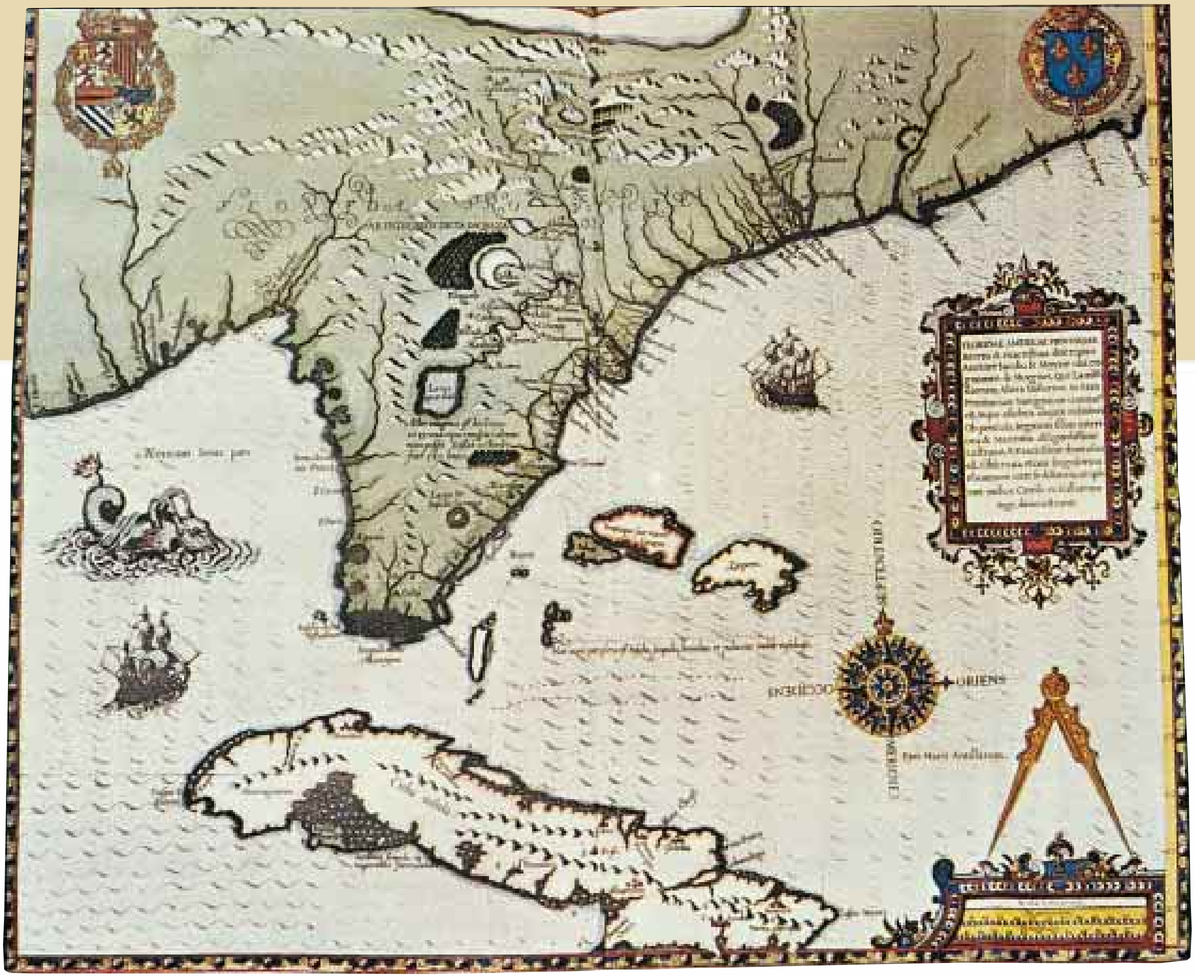
by Clark Spencer Larsen

The lives of Native Americans changed in dramatic ways after Christopher Columbus landed in the Caribbean islands in 1492. Written records paint a vivid picture of conquest and epidemics sowing death and disease among the indigenous peoples of the Americas, quickly decimating them. Until recently, in fact, almost all that was known about the biological consequences of contact with the Europeans was based on these old documents, which emphasize epidemics and population collapse. Although these texts offer an important perspective, they are not the only source of information.

Bioarchaeology, an emerging field that focuses on the study of archaeological remains, is supplementing our view of the health and daily life of Native Americans, particularly those who lived in the Spanish missions of the Southeast, in an area once known as *La Florida*. Sustained encounters between Indians and Europeans in *La Florida* began in 1565, when Pedro Menéndez de Avilés established the town of St. Augustine on the Atlantic coast in northern Florida. From there Roman Catholic priests set up a chain of missions among the Timucua and Apalachee Indians of northern Florida and the Guale Indians of the Georgia coast. At some of those places—including Santa Catalina de Guale on St. Catherines Island, San Martín de Timucua and San Luis de Apalachee—archaeologists have uncovered the ruins of large churches that served the converts. As the nucleus of each community, the church carried out important religious functions for the living; for the dead, it provided a burial ground.

Skeletons found beneath the floor of these churches have provided scholars with a surprisingly complete record of the diet and work habits of the mission Indians. Bioarchaeology is beginning to fill in the details of the historical record, offering specifics about how food sources changed and raising unexpected questions about the merits of a purely agricultural

JOHN WHITE



LA FLORIDA **was viewed by the Spanish as fertile land for conquest, and the region's natives as souls to be converted and workers to be harnessed—particularly for the harvest of corn, which became increasingly important as a dietary staple (*far left*).**

FROM *BREVIS NARRATIO* (1591), BY JACQUES LE MOYNE

way of life—at least for the Indians who inhabited *La Florida*.

Food, obviously, is fundamental to human well-being, as it provides nutrients for growth, development and other physiological processes. Before our research, the diets of *La Florida* Indians were reconstructed from two sources: accounts by priests and other Europeans, and food remains at archaeological sites. The written records are often contradictory. Some depict little farming at the time. Others, including those examined by Grant D. Jones of Davidson College, say that indigenous peoples relied heavily on agriculture, particularly on corn.

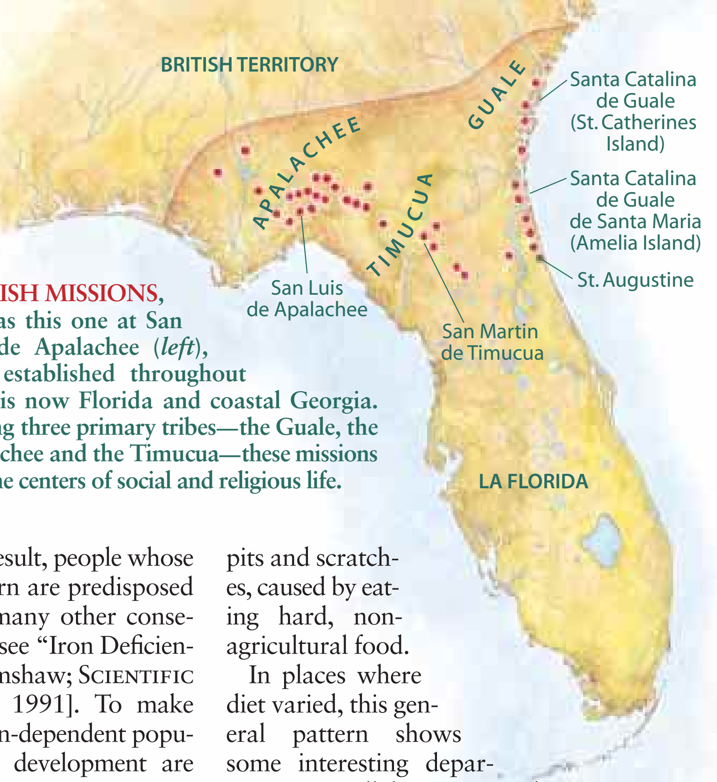
The archaeological record is inconclusive as well. Plant remains do not always survive well, and in coastal regions they are particularly vulnerable to the destructive effects of moisture and acidic soils. Nevertheless, analysis of such evidence by C. Margaret Scarry of the University of North Carolina at Chapel Hill and Donna Ruhl of the University of Florida has revealed that native peoples ate numerous plant species, both wild and domesticated, before and after the arrival of the Europeans. But their use of corn is unclear. Excavations have revealed some kernels and cobs from late prehistoric and contact-era sites; however, the relative importance of this grain in the Indians' diet is not known.

Reconstructing Diet

To resolve some of these questions, we turned to the many bones found at these sites. Because the tissues of all living things contain stable isotopes of such elements as carbon and nitrogen, we can measure the amounts of these elements in bones and then use this information to reconstruct ancient diets. Differences in the ratios of two carbon isotopes, carbon 12 and carbon 13, contain a record of which plants an individual ate. Most plants are divided into two types: carbon 3 plants break down a three-carbon molecule during photosynthesis; carbon 4 plants synthesize a four-carbon molecule. The distinctive chemical signature of the C_3 and C_4 plants that a person consumes shows up in his or her bones. Virtually all plants eaten in the *La Florida* region were of the C_3 variety—including fruits, wheat, acorns and hickory nuts. The only major C_4 plant eaten by native peoples was corn.

Nitrogen isotopes provide a different set of clues. Fish bones and oyster shells in archaeological sites indicate that the Guale and other native peoples of the region ate seafood regularly—before and after the Europeans arrived. Because marine plants, such as algae, and terrestrial plants use the two stable isotopes of nitrogen—nitrogen 14 and nitrogen 15—differently, the ratios of these isotopes are different in the bones of a person who ate mostly marine foods as opposed to one who ate mostly terrestrial foods.

Examining the differences between carbon and nitrogen ratios in bones before and after the Europeans arrived pointed to enormous changes in the Native Americans' diets. Margaret J. Schoeninger of the University of Wisconsin–Madison, Nikolaas J. van der Merwe of Harvard University, Dale L. Hutchinson of East Carolina University, Lynette Norr of the University of Florida and I found that the variations were geographically and chronologically patterned. As would be ex-



SPANISH MISSIONS, such as this one at San Luis de Apalachee (*left*), were established throughout what is now Florida and coastal Georgia. Serving three primary tribes—the Guale, the Apalachee and the Timucua—these missions became centers of social and religious life.

pected, coastal people ate more seafood than inland people did, regardless of the era. The Guale Indians on St. Catherines and Amelia islands ate corn before and after the missionaries arrived. But during the mission period, they ate more than their ancestors had. Similarly, the Apalachee, who had eaten some corn before contact, seemed to eat it more after the Europeans arrived; and the Timucua, who had eaten little or no corn before contact, also adopted it after the establishment of the missions.

The Consequences of Corn

The bone chemistry findings thus show that the Indians' diets changed after the Europeans came—but not for the better. Their relatively heterogeneous diet, rich in seafood and a variety of plants and animals, was replaced by a more homogeneous and less nutritious diet focused on the cultivation of a single crop: corn.

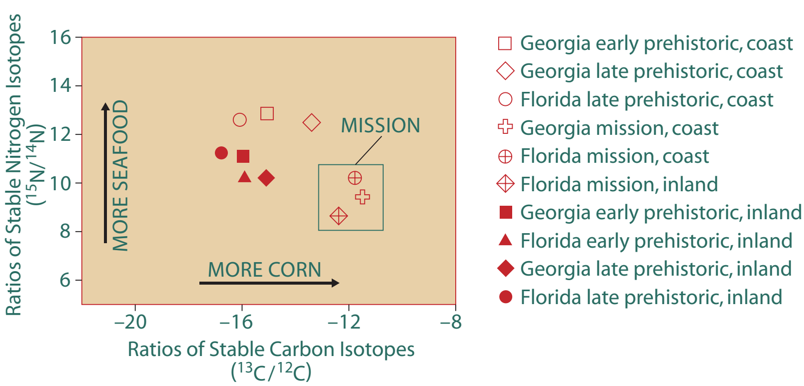
Corn-dominated diets are very poor ones. Corn contains a great deal of sugar, which promotes cavities and poor oral health in general. It also contains phytate, a chemical that binds with iron, inhibiting absorption of the mineral by the body. As a result, people whose diets are heavy in corn are predisposed to anemia and the many other consequences of low iron [see "Iron Deficiency," by Nevin S. Scrimshaw; SCIENTIFIC AMERICAN, October 1991]. To make matters worse for corn-dependent populations, growth and development are hampered because corn is a poor source of calcium and of niacin, or vitamin B_3, which is necessary for metabolism. Corn is also an inadequate source of protein because, depending on the strain, it is deficient in or entirely lacking three of the eight essential amino acids: lysine, isoleucine and tryptophan.

For these reasons, some mission Indians have more, and larger, cavities than their ancestors did. Tooth decay was probably exacerbated by the consistency of their food: soft foods, such as gruel made from corn, facilitate the buildup of cavity-causing bacteria and plaque on teeth. By looking at tooth wear with a scanning electron microscope, Mark F. Teaford and his colleagues at Johns Hopkins University have shown that the foods eaten by mission Indians were softer than those their ancestors ate. We can tell this by the reduction in the number of tooth-surface features, such as pits and scratches, caused by eating hard, nonagricultural food.

In places where diet varied, this general pattern shows some interesting departures. In collaboration with Bonnie G. McEwan of the Florida Bureau of Archaeological Research, we analyzed teeth from the San Luis mission site. Later work on the teeth by Tiffiny A. Tung of the University of North Carolina at Chapel Hill indicated that people in this mission had fewer cavities than did their counterparts at other sites. This departure from the usual pattern may have been explained by the research of Elizabeth J. Reitz of the University of Georgia, who examined animal remains at the same site. She determined that people living in San Luis had access to beef—a rare addition to the mission Indians' standard diet—and that protein may have inhibited the formation of cavities.

The tooth record has provided us with other important insights as well. Hutchison and I have found that many Indians had hypoplasias—visible lines on teeth caused by disease or malnutrition. The large size of the hypoplasias in some Indians suggests that they experienced severe or sustained illness or poor nutrition, or both. We also found evidence of disturbances in tooth development. With Scott W. Simpson of Case Western Reserve University, we studied microscopic features of teeth, looking at what are called Retzius lines—growth lines that can be seen in enamel. Although both precontact and mission Indians have abnormal Retzius lines, these malformations are more prevalent in the mission Indians.

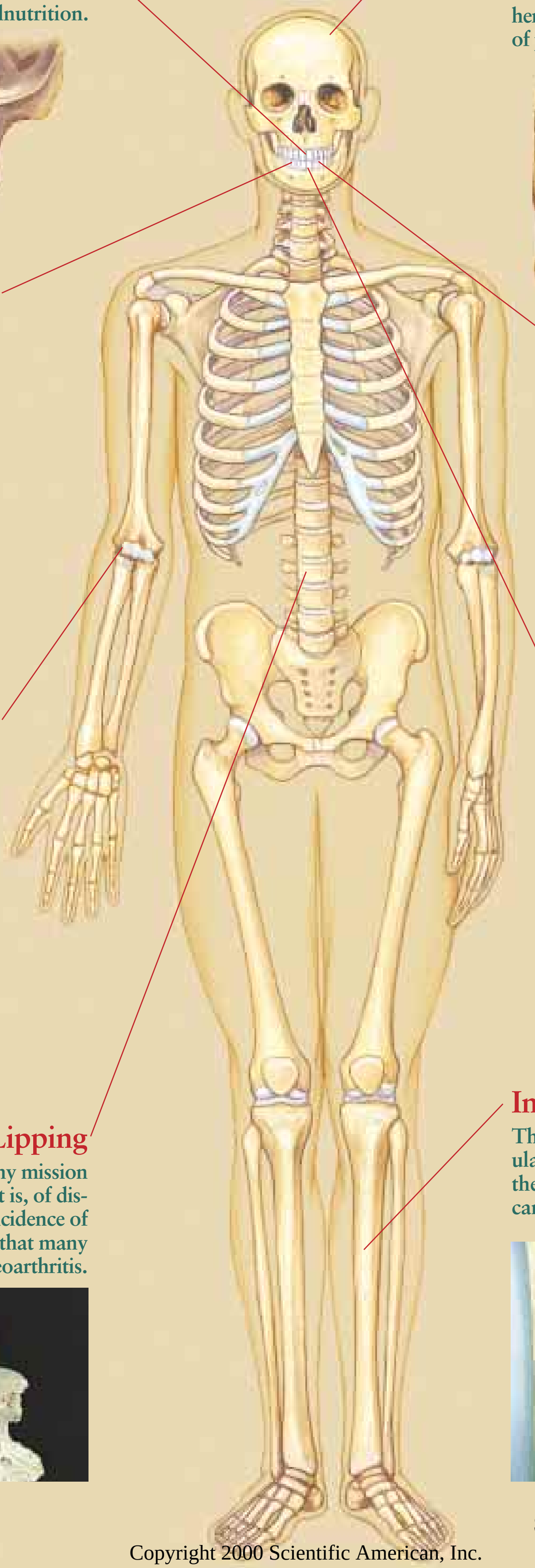
Considered together with other evidence, the increase in abnormal Retzius



RATIOS OF ELEMENTS, such as carbon and nitrogen isotopes, provide important information about diet. Recorded in bones, these varying ratios reveal what kinds of plants or how much seafood an individual ate.

EDWARD JONAS AND THE FLORIDA DIVISION OF HISTORICAL RESOURCES (*painting*); ROBERTO OSTI (*map*); BRYAN CHRISTIE (*graph*)

Signs of Stress in a Skeleton



Hypoplasias

These lines on the teeth of postcontact Indians are the telltale signs of disease and malnutrition.

Tooth Microwear

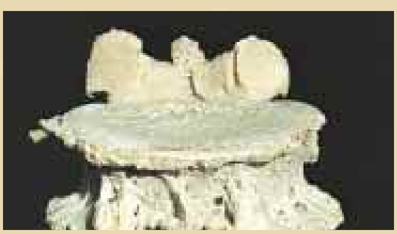
The teeth of mission Indians are smoother (*left*) than those of their ancestors (*right*), suggesting that the later diet centered on soft foods, such as corn gruel, which promote the buildup of plaque and cavity-causing bacteria.

Osteoarthritis: Joint Polish

Excessive wear and tear on a skeleton can be detected in several places, including the joints. Polishing of the joints indicates that cartilage was worn down and that the joint surface had deteriorated.

Osteoarthritis: Lipping

The vertebrae of the lower back in many mission Indians show evidence of lipping—that is, of distortion from heavy lifting. The incidence of lipping and the joint polish suggest that many adult workers suffered from osteoarthritis.

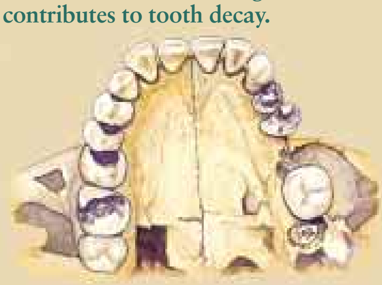


Anemia and Porotic Hyperostosis

Corn contains phytate, which inhibits the absorption of iron. As a result, many mission Indians suffered from anemia and their bones have sievelike lesions that can be seen on the skull and in a microscopic close-up. In nonanemic individuals the dark bands would be much thicker than those shown here (*right*). (These lesions may also be the result of parasitic infection.)

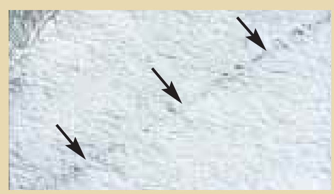
Dental Cavities

Cavities were common in Indians who ate a lot of corn—a grain that contributes to tooth decay.



Retzius Lines

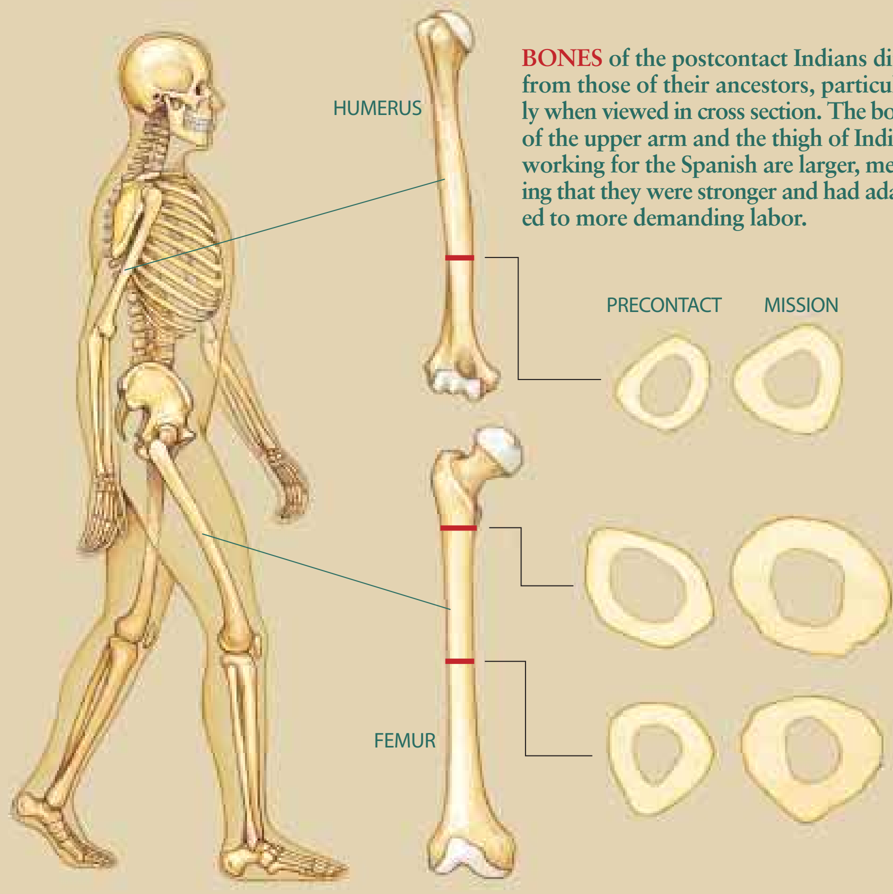
These growth lines can be seen in tooth enamel. In many of the mission Indians they are abnormally dark, indicating that poor diet and disease were common.



Infection

The lower leg bones, or tibiae and fibulae, of many of the Indians living in the missions have visible lesions. These can be caused by bacterial infections.

ROBERTO OSTI (*skeleton; dental cavities; anemia drawing; hypoplasias*); MARK TEAFORD (*tooth microwear*); BARRY STARK (*osteoarthritis: joint polish and osteoarthritis: lipping*); MARK C. GRIFFIN (*infection*); MICHAEL SCHULTZ (*anemia photograph*); SCOTT W. SIMPSON (*Retzius lines*)



BONES of the postcontact Indians differ from those of their ancestors, particularly when viewed in cross section. The bones of the upper arm and the thigh of Indians working for the Spanish are larger, meaning that they were stronger and had adapted to more demanding labor.

lines suggests that poor diet was not the only problem facing the mission Indians. David Hurst Thomas of the American Museum of Natural History in New York City has excavated a shallow, plank-lined well in Santa Catalina de Guale that may have served as a reservoir for parasites. Although their ancestors relied on freshwater streams and springs, the mission Indians drank well water, and anyone living in the region today knows the dangers of drinking water from shallow wells: it is easily contaminated and can cause parasitic infection and other problems.

The probability of rampant infection is strengthened by the fact that most of the defective tooth enamel we studied appears to have been formed during the first two years of life. This is a period when dehydration from infantile diarrhea is a primary health threat. Acute dehydration can inhibit the function of all forms of cells, including ameloblasts—the cells responsible for enamel formation. As in many underdeveloped nations today, bacteria and viruses in contaminated food and water cause infantile diarrhea. Certainly the mission would have created the kind of living circumstances that promote infantile diarrhea and the pattern of growth stress we have seen in teeth.

Other diseases, such as smallpox and measles, may have easily spread as well because the Indians were clustered together in crowded communities around the missions. Although many acute infectious diseases kill people long before their bones are affected, some infections—such as those caused by the bacterium *Staphylococcus aureus*—can travel from a soft-tissue wound to nearby bone, leaving observable lesions. Numerous lower-leg bones, or tibias, of contact-era Indians have lesions that suggest just this kind of infection.

Infection can also cause anemia because some types of parasite, such as hookworm, bleed their human hosts. Observations of mission bones indicate that such infection was common. The surfaces of many of these bones have sievelike lesions—called porotic hyperostosis—that can be caused by iron deficiency, scurvy or infection. Few precontact Indians seemed to have these lesions, probably because their diet of fish and maize together provided enough iron to stave off anemia. But the abundance of porotic hyperostosis in the mission Indians was most likely the result of the anemia brought on not simply by an increasingly corn-rich diet but also by intestinal infection.

Food and living conditions were not the only aspects of culture that were drastically altered for the Indians who lived in the missions. The Spanish practiced *repartimiento* draft labor in *La Florida*, which meant that able-bodied Indian men were required to work on farms, in public works and government building projects, and for the military. Indians were also required to carry heavy loads over long distances, because draft animals were not available in the region until after 1680 or thereabouts. In our studies of skeletons, we noticed that contact-era Indians had a higher rate of osteoarthritis than their predecessors did—a phenomenon we believed had been caused by the increased workload, because wear and tear on the joints can lead to osteoarthritis. But the condition is related to other factors as well. So we decided to investigate further, looking to the skeletons for more answers.

Working Bones

The skeleton of a living person is highly responsive to physical activity. Throughout life a person's bones change shape and structure in response to mechanical forces acting on them. Basically, bone tissue is placed where the skeleton needs it. When a person walks, for example, or stands, forces deriving from the pull of muscles or from body weight trigger cellular activity in the bone that results in skeletal remodeling. Without the proper amount or distribution of bone in key places, the force of bending or twisting could break the thigh bone, or femur.

Drawing from methods developed by civil and mechanical engineers for measuring the strength of building materials, Christopher B. Ruff of the Johns Hopkins University School of Medicine and I have analyzed the strength of femur and humerus (upper-arm) bones from both precontact and mission sites in *La Florida*. This approach entails measuring cross-sectional geometric properties of the bones called second moments of area. Second moments of area reflect how the bone is distributed in cross section and indicate the strength or ability of the bone to resist breaking during bending or twisting. The analysis entails tracing the profile of the outer (subperiosteal) and inner (endosteal) perimeters of the bones in cross section and then calculating the biomechanical properties of the bone [*see illustration above*].

We discovered that the mission Indi-

ROBERTO OSTI

AGRICULTURE among the mission Indians, such as the Timucua depicted in this 16th-century engraving, increased enormously after the Spanish arrived. The shift was not beneficial for the natives of *La Florida.* Agriculture ultimately forced them to simplify their diet to such a degree that their health suffered.

ans had stronger bones than their predecessors did: the later bones had greater second moments of area than the earlier bones. This is not to say that the bones of the mission Indians were better than those of their ancestors. Rather the bones had just adapted to new mechanical demands. Given the well-known circumstance of exploitation and the heavy workloads of the Indians laboring under the Europeans, we believe that the increases in bone strength and osteoarthritis were caused by fundamental alterations in their way of life that involved increased physical activity.

The insights afforded us by bioarchaeology confirm much of what is found in historical texts—including the forced labor of the Indians and the diseases that plagued them—but they also give us a much more comprehensive and precise picture of the past. European contact introduced hardships for the Indians on many fronts. Pestilence, poor nutrition, iron deficiency, growth disruption, infection and hard labor all took their toll. Yet despite the unfavorable state of affairs, native peoples accommodated new demands and new challenges, a story that is repeated time and again in the history of our species. SA

The Author

CLARK SPENCER LARSEN directs the La Florida Bioarchaeology Project, which involves the collaboration of many scientists from the U.S. and abroad. He began his studies of ancient human skeletons in his freshman year at Kansas State University, where he received his B.A. in 1974. His doctorate in biological anthropology was awarded by the University of Michigan in 1980. Larsen is Ames Hawley Professor of Anthropology at the University of North Carolina at Chapel Hill and is a research associate with the American Museum of Natural History in New York City. Larsen is currently president of the American Association of Physical Anthropologists.

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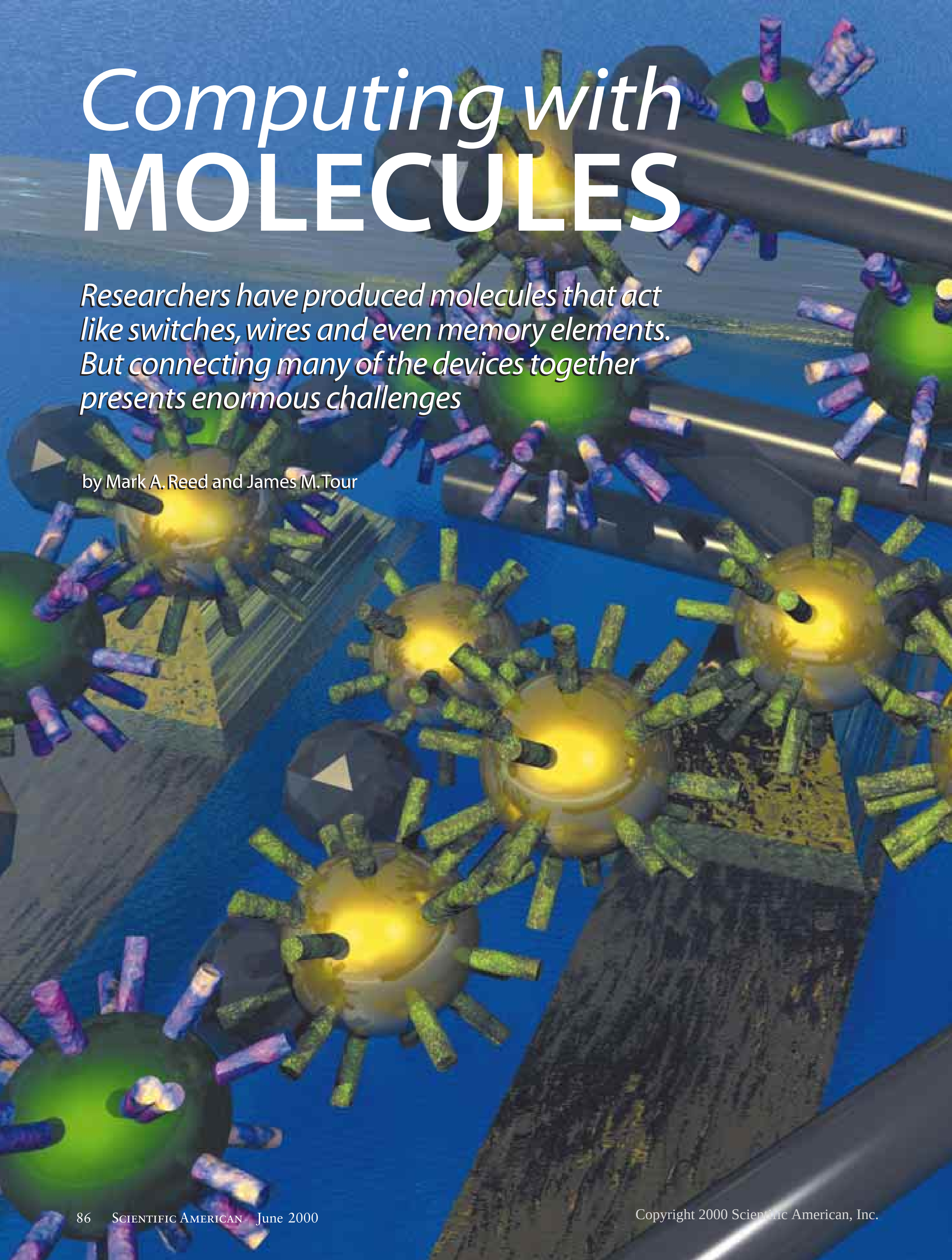
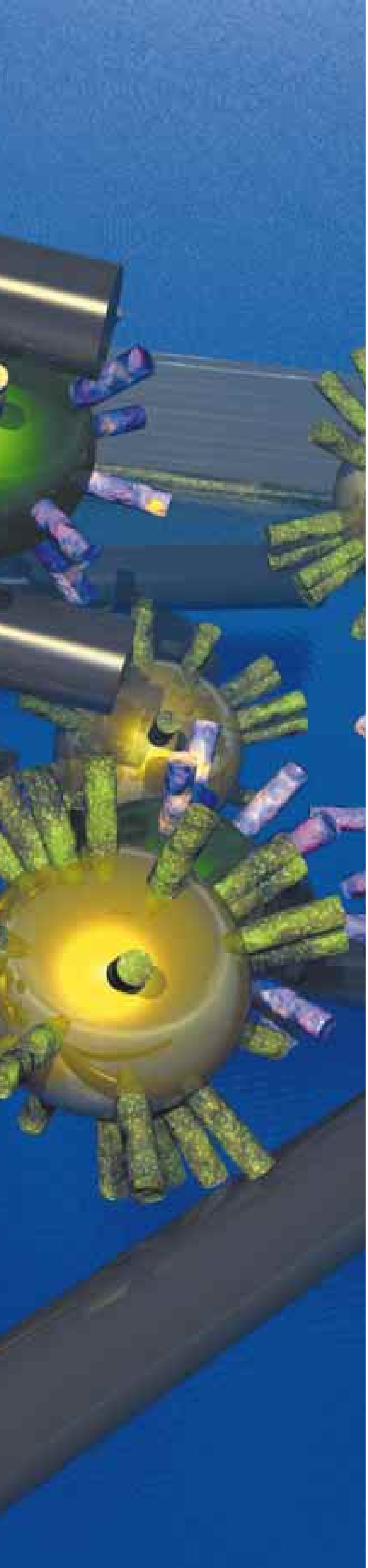
FROM *BREVIS NARRATIO* (1591), BY JACQUES LE MOYNE

Computing with MOLECULES

Researchers have produced molecules that act like switches, wires and even memory elements. But connecting many of the devices together presents enormous challenges

by Mark A. Reed and James M. Tour





How fast and powerful can computers become? Will it be possible someday to create artificial "brains" that have intellectual capabilities comparable—or even superior—to those of human beings? The answers to these questions depend to a very great extent on a single factor: how small and dense we can make computer circuits.

Few if any researchers believe that our present technology—semiconductor-based solid-state microelectronics—will lead to circuitry dense and complex enough to give rise to true cognitive abilities. And until recently, none of the technologies proposed as successors to solid-state microelectronics had shown enough promise to rise above the pack. Within the past year, however, scientists have achieved revolutionary advances that may very well radically change the future of computing. And although the road from here to intelligent machines is still rather long and might turn out to have unbridgeable gaps, the fact that there is a potential path at all is something of a triumph.

The recent advances were in molecular-scale electronics, a field emerging around the premise that it is possible to build individual molecules that can perform functions identical or analogous to those of the transistors, diodes, conductors and other key components of today's microcircuits. After a period of high hopes but few tangible results, several developments over the past few years have raised expectations that this technology may one day provide the building blocks for future generations of ultrasmall, ultradense electronic computer logic. In a remarkable series of demonstrations, chemists, physicists and engineers have shown that individual molecules can conduct and switch electric current and store information.

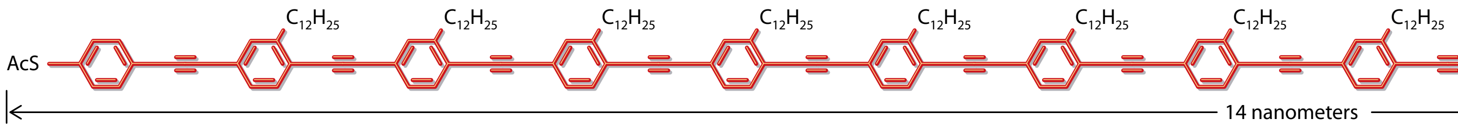
Last July, in an achievement widely reported in the popular press, researchers from Hewlett-Packard and the University of California at Los Angeles announced that they had built an electronic switch consisting of a layer of several million molecules of an organic substance called rotaxane. By linking a number of switches, the researchers produced a rudimentary version of an AND gate, a device that performs a basic logic operation. With well over a million molecules apiece, the switches are far larger than would be desirable. And they could be switched only one time before becoming inoperable. Nevertheless, their assembly into a logic gate was of fundamental significance.

Within months of that announcement, our groups at Yale and Rice universities published results on a different class of molecules that acted as a reversible switch. And one month later we described a molecule we had created that could change its electrical conductivity by storing electrons on demand, acting as a memory device.

To produce our switch, we inserted regions into the molecules that trapped electrons, but only when the molecules were subjected to certain voltages. Thus, the degree to which the molecules resisted a flow of electrons depended on the voltage applied to them. In fact, by varying the voltage, we could repeatedly change the molecules at will from a conducting to a nonconducting state—which is the basic requirement for an electrical switch. The

MARK A. REED

MOLECULAR ELECTRONICS CIRCUIT might look like this conception by one of the authors (Reed). The molecular devices are the tiny cylindrical items emerging from the spheres, which are either semiconductor particles acting as memory elements (*green*) or gold particles acting as electrical connectors. Larger black rods in the illustration are carbon nanotubes, also acting as electrical connectors. The larger black rectangular pads are lithographically fabricated connectors to larger external circuits of a more conventional nature.



LONG MOLECULE is a potential "wire" for connecting molecular devices. One of the authors (Tour) produced the molecule using a new synthesis technique. Researchers are still figuring out how to insert such a long molecule between two electrical connectors in order to test its current-carrying capacity.

tiny device actually consisted of a layer of about 1,000 molecules of nitroamine benzenethiol sandwiched between metal contacts.

After creating the switch, we realized that if we could redesign the molecule so that it could retain electrons rather than trapping them briefly, we would have something that could work as a memory element. We went to work on the trapping region of the molecule, modifying it so that its conductivity could be changed repeatedly. The resulting "electron sucker" could retain electrons for nearly 10 minutes—compared with a few milliseconds for conventional silicon-based dynamic random-access memory.

Although the advances were encouraging, the challenges remaining are enormous. Creating individual devices is an essential first step. But before we can build complete, useful circuits we must find a way to secure many millions, if not billions, of molecular devices of various types against some kind of immobile surface and to link them in any manner and into whatever patterns our circuit diagrams dictate. The technology is still too young to say for sure whether this monumental challenge will ever be surmounted.

The End of the Road Map

Given the magnitude of the challenges ahead, why did researchers and even the mainstream media pay so much attention to the recent advances? The answer has to do with industrial society's dependence on microelectronics—and the limits of the form of the technology we have today.

That form—solid-state and silicon-based—follows one of the most famous axioms in technology: Moore's Law. It relates that the number of transistors that can be fabricated on a silicon integrated circuit—and therefore the computing speed of such a circuit—is doubling every 18 to 24 months. After following this remarkable curve for four decades, solid-state microelectronics has advanced to the point at which engineers can now put on a sliver of silicon of just a few square centimeters some 100 million transistors, with key features measuring 0.18 micron.

These transistors are still far larger than molecular-scale devices. To put the size differential in perspective, if the conventional transistor were scaled up so that it occupied the printed page you are reading, a molecular device would be the period at the end of this sentence. Even in a dozen years, when industry projections suggest that silicon transistors will have shrunk to about 120 nanometers in length, they will still be more than 60,000 times larger in area than molecular electronic devices.

Moreover, no one expects conventional silicon-based microelectronics to continue following Moore's Law forever. At some point, chip-fabrication specialists will find it economically infeasible to continue scaling down microelectronics. As they pack more transistors onto a chip, phenomena such as stray signals on the chip, the need to dissipate the heat from so many closely packed devices, and the difficulty of creating the devices in the first place will halt or severely slow progress.

Indeed, various nagging (though not yet fundamental) problems in the fabrication of efficient smaller silicon transistors and their interconnections are becoming increasingly bothersome. Many experts expect these challenges to intensify dramatically as the transistors approach the 0.1-micron level. Because of these and other difficulties, the exponential increase in transistor densities and processing rates of integrated circuits is being sustained only by a similar exponential rise in the financial outlays necessary to build the facilities that produce these chips. Eventually the drive to downscale will run headlong into these extreme facility costs, and the market will reach equilibrium. Many experts project that this will happen around or before 2015, when a fabrication facility is projected to cost nearly $200 billion. When that happens, the long period of breathtaking advances in the processing power of computer chips will have run its course. Further increases in the power of the chips will be prohibitively costly.

Unfortunately, this impasse will almost certainly occur long before computer chips have reached the power to fulfill some of the most sought-after goals in computer science, such as the creation of extremely sophisticated electronic "brains" that will enable robots to perform on a par with humans in intellectual and cognitive tasks.

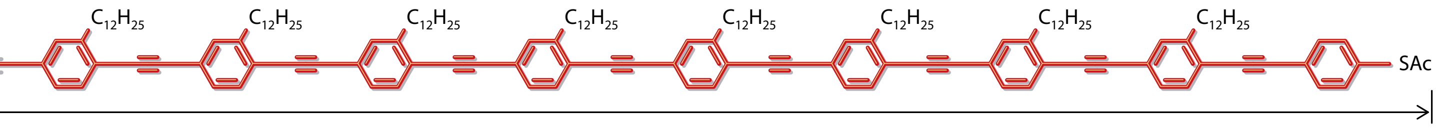
Billions and Billions

The extraordinarily small size of molecular devices brings advantages beyond the simple ability to pack more of them into a small area. To grasp these important benefits requires an understanding of how the devices work—which in turn demands some knowledge of how electrons behave when confined to regions as small as atoms and molecules.

Free electrons can take on energy levels from a continuous range of possibilities. But in atoms or molecules, electrons have energy levels that are quantized: they can only be any one of a number of discrete values, like rungs on a ladder. This series of discrete energy values is a consequence of quantum theory and is true for any system in which the electrons are confined to an infinitesimal space. In molecules, electrons arrange themselves as bonds among atoms that resemble dispersed "clouds," called orbitals. The shape of the orbital is determined by the type and geometry of the constituent atoms. Each orbital is a single, discrete energy level for the electrons.

Even the smallest conventional microtransistors in an integrated circuit are still far too large to quantize the electrons within them. In these devices the movement of electrons is governed by physical characteristics—known as band structures—of their constituent silicon atoms. What that means is that the electrons are moving in the material within a band of allowable energy levels that is quite large relative to the energy levels permitted in a single atom or molecule. This large range of allowable energy levels permits electrons to gain enough energy to leak from

JARED SCHNEIDMAN DESIGN



one device to the next. And when these conventional devices approach the scale of a few hundred nanometers, it becomes extremely difficult to prevent the minute electric currents that represent information from leaking from one device to an adjacent one. In effect, the transistors leak the electrons that represent information, making it difficult for them to stay in the "off" state.

Building from the Bottom Up

Besides enabling molecular devices to contain their electrons more securely, quantum mechanical phenomena can also be exploited in specially designed molecules to perform other functions. For example, to construct a "wire" we need an elongated molecule through which electrons can flow easily from one end to the other. Electrons in any quantized structure such as a molecule tend to move from higher- to lower-energy levels, so in order to channel electrons we need a molecule that has an empty, low-energy orbital that is dispersed throughout the molecule from one end to the other. A typical empty, low-energy electron orbital is known as a pi orbital. And the configuration in which electron clouds overlap from one molecular component to the next is called conjugated, so our molecular wire is known as a "pi-conjugated system."

An active device such as a transistor, however, has to do more than merely allow electrons to flow—it has to somehow control that flow. Thus, the task of the molecular device engineer is to exploit the quantum world's discrete energy levels—specifically, by designing molecules whose orbital characteristics achieve the desired kind of electronic control. For example, with the right overlap of orbitals in the molecule, electrons flow. But when the overlap is disturbed—because the molecule has been twisted or its geometry has been otherwise affected—the flow is blocked. In other words, the key to control on the molecular scale is manipulating the number of electrons that are allowed to flow at low orbital energy by perturbing the orbital overlap through the molecule.

Already the standard methods of chemical synthesis allow researchers to design and produce molecules with specific atoms, geometries and orbital arrangements. Moreover, enormous quantities of these molecules are created at the same time, all of them absolutely identical and flawless. Such uniformity is extremely difficult and expensive to achieve in other batch-fabrication processes, such as the lithography-based process used to produce the millions of transistors on an integrated circuit.

The methods used to produce molecular devices are the same as those of the pharmaceutical industry. Chemists start with a compound and then gradually transform it by adding prescribed reagents whose molecules are known to bond to others at specific sites. The procedure may take many steps, but gradually the pieces come together to form a new potential molecular device with a desired orbital structure. After the molecules are made, we use analytical technologies such as infrared spectroscopy, nuclear magnetic resonance and mass spectrometry to determine or confirm the structure of the molecules. The various technologies contribute different pieces of information about the molecule, including its molecular weight and the connection point or angle of a certain fragment. By combining the information, we determine the structure after each step as the new molecule is synthesized.

One of our simplest active devices was a molecule based on a string of three benzene rings, in which the orbitals overlapped (were conjugated) throughout. We made the connections between the benzene rings structurally weak, so that slight twists or kinks weakened or strengthened the conjugation of the orbitals. All we needed was a way to control this twisting and we would have a molecular device in which we could control current flow—a switch, in other words.

To the center benzene ring in the molecule, we added NO_2 and NH_2 groups, projecting outward from the string on opposite sides of the center ring. This asymmetrical configuration left the molecule with a strongly perturbed electron cloud. That asymmetric, perturbed cloud in turn made the molecule very susceptible to distortion by an electric field: applying an electric field to the molecule twisted it. We now had an active device: every time we applied a voltage to the molecule, an electric field was set up that twisted the molecule and blocked current flow. With the voltage removed, the molecule sprang back to its original shape, and the current flowed again. In follow-up experiments, we found that for our infinitesimal device the abruptness of the switching from one state to the other was superior to that of any comparable solid-state device.

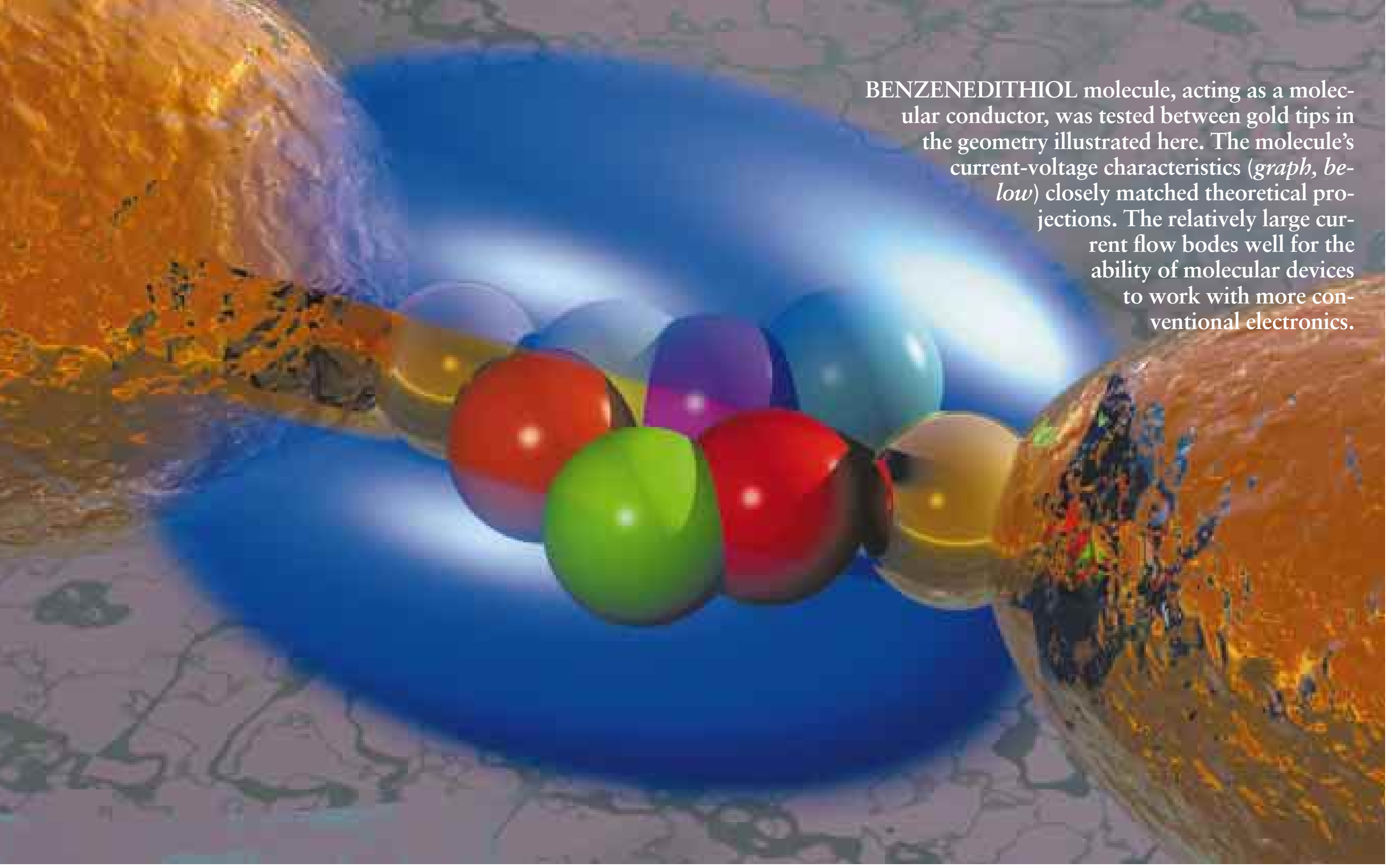
Of course, a lot of advanced technology and years of research were necessary before we could even test one of these

The Basics

The inexorable drive to produce smaller devices may leave technologists no choice but to migrate to a new form of electronics in which specially designed individual molecules replace the transistors of today's circuits. That forced migration could come about within the next decade, some researchers believe.

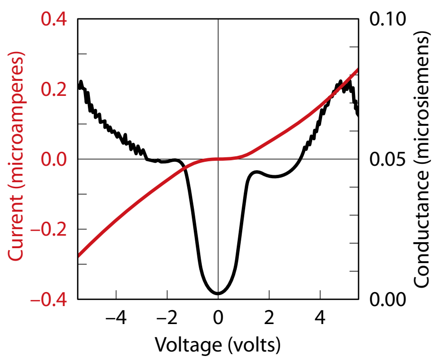
The bare requirements for a general-purpose computer are a switching device (like a transistor), memory and a way of connecting arbitrarily large numbers of the devices and memory elements. So far scientists have managed to produce single-molecule switches and memory elements. The switch, however, had only two terminals. Realistically, to construct complex logic circuits requires a device with more than two terminals, in which, for example, current flow between two is controlled by a third (that is the way transistors work).

Even more imposing, scientists lack a method of connecting huge numbers of the devices. Although no potential solutions to this problem are apparent yet, researchers suspect that radically new architectures and conventions will be needed to exploit molecular devices fully.



BENZENEDITHIOL molecule, acting as a molecular conductor, was tested between gold tips in the geometry illustrated here. The molecule's current-voltage characteristics (*graph, below*) closely matched theoretical projections. The relatively large current flow bodes well for the ability of molecular devices to work with more conventional electronics.

MARK A. REED



JARED SCHNEIDMAN DESIGN

devices. The basic challenge is reaching into an unfathomably Lilliputian domain in order to contact and interact with a single molecule and bring information about the behavior of that molecule into our macroscopic world.

The task was all but impossible before the invention, in the 1980s, of the scanning tunneling microscope (STM) at IBM's research laboratories in Zurich. The STM gives scientists a window on the atomic world, letting them visualize and manipulate single atoms or molecules. With an atomically sharp tip of metal held precisely over a surface, the topography of the surface is sensed by the minute current of tunneling electrons that flows between the surface and the tip. Rastering the tip back and forth creates a picture of the hills and valleys on the surface.

Although scanning tunneling microscopy is crucial for testing and constructing individual devices, any useful molecular circuit will consist of vast numbers of devices, orderly arranged and securely affixed to a solid structure to keep them from interacting randomly with one another. Progress toward solving this huge challenge has emerged from studies of self-assembly, a phenomenon in which atoms, molecules or groups of molecules arrange themselves spontaneously into regular patterns and even relatively complex systems without intervention from outside.

Molecular Glue

Once the assembly process has been set in motion, it proceeds on its own to some desired end [see "Self-Assembling Materials," by George M. Whitesides; Scientific American, September 1995]. In our research we use self-assembly to attach extremely large numbers of molecules to a surface, typically a metal one [*see illustration on page 92*]. When attached, the molecules, which are often elongated in shape, protrude up from the surface, like a vast forest with identical trees spaced out in a perfect array.

Researchers have studied a variety of self-assembly systems. Our work often requires us to attach molecular devices to a metal (usually gold) surface. So we frequently work with a molecular fragment that we attach to one or both ends of our device and that has a high affinity for gold atoms. The specific fragment we commonly use, called a "sticky" end group for obvious reasons, is based on an atom of sulfur and is known in chemical terminology as thiol.

To initiate the self-assembly, we need only dip a gold surface into a beaker. In solution in this container are our molecular devices, each with thiol end groups on both ends. Spontaneously and in unimaginably large numbers, the devices attach themselves to the gold surface.

Handy though it is, self-assembly alone will not suffice to produce useful molecular-computing systems, at least not initially. For some time, we will have to combine self-assembly with fabrication methods, such as photolithography, borrowed from conventional semiconductor manufacturing. In photolithography, light or some other form of electromagnetic radiation is projected through a stencil-like mask to create patterns of metal and semiconductor on the surface of a semiconducting wafer. In our research we use photolithography to generate layers of metal interconnections and also holes in deposited insulating material. In the holes, we create the electrical contacts and selected spots where molecules are constrained to self-assemble. Thus, the final system consists of regions of self-assembled molecules attached by a mazelike network of metal interconnections.

The first successful demonstration of self-assembly in molecular electronics occurred just four years ago, in 1996, when Paul S. Weiss's group at Pennsylvania State University tested self-assembled molecules. One of us (Tour), then at the University of South Carolina, synthesized the devices. Weiss and his colleagues found that by mixing a small amount of a solution of molecules that were designed to have conducting properties with another containing a known inert insulating molecule, they could get a self-assembled layer in which conductive molecules were very sparsely interspersed among nonconductive ones. By positioning the tip of an STM directly over one of the isolated conducting molecules, they could qualitatively measure the conductivity. As expected, it was significantly greater than that of the surrounding molecules. Similar results were also obtained by a group at Purdue University, which tagged the top of the conductive molecules with minute gold particles.

At the same time at Yale, one of us (Reed) performed the first quantitative electrical measurements of a single molecule, which was also fabricated by self-assembly. Specifically, Reed and his group measured how much current could flow across a single molecule. The heart of the experimental setup was an STM modified to enable it to position two tips opposite each other with sufficient precision and mechanical stability to contain a single molecule in between [*see illustration on opposite page*]. A very simple molecule was used to convey mobile electrons: a single benzene ring with sticky thiol end groups on both ends to contact the metal leads of the STM tips. It turned out that the resistance of the molecule was in the range of tens of millions of ohms.

The Yale researchers also found that the molecule could sustain a current of about 0.2 microampere at five volts—which meant that the molecule could channel through itself roughly a million million (10^{12}) electrons per second. The number is impressive—all the more so in light of the fact that the electrons can pass through the molecule only in single file (one at a time). The magnitude of the current was far larger than would be expected from simple calculations of the power dissipated in a molecule, leading to the conclusion that the electrons traveled through the molecule without generating heat by interacting or colliding.

These initial observations of conduction in molecules were followed quickly by demonstrations of basic devices. The simplest electronic device is a diode, which can be thought of as a one-way valve for electrons. In 1997, only a year after the first measurements of conduction in molecules, two separate research groups built diodes. At the University of Alabama, Robert M. Metzger's group synthesized a molecule that had an internal energetic lineup of orbitals, which varied depending on the polarity of the voltage applied to it. The lineup of orbitals was analogous to the rungs on a ladder. With the voltage applied in one direction, the lineup corresponded to a ladder propped against a house. In this orientation, it takes considerable effort to climb the ladder. With the opposite voltage polarity, the orbital lineup was analogous to the rungs of a ladder lying flat on the ground, where it can be traversed with little effort.

In the other group at Yale, Chong-Wu Zhou took a slightly different tack. With this molecular diode, the differences in the lineup of the energy levels occurred externally to the molecule, where it contacted the metal. This scheme also worked well and helped to set the stage for the design of more useful and interesting molecular devices and circuits.

Radical departures from present computing design will probably be needed to exploit molecular computing systems fully.

Connecting from the Top Down

As they began constructing such devices, the Yale group adapted a structure first made by Kristin Ralls and Robert A. Buhrman of Cornell University. The structure contained an extremely minute hole, called a nanopore, in which an "active region" was created by self-assembling a relatively small number of molecular devices in a single layer, or monolayer. In a hole just 30 nanometers wide, approximately 1,000 of the molecular devices were allowed to self-assemble. Evaporating a metal contact onto the top of the self-assembled monolayer ("SAM") completed the device.

After using this configuration to produce and test molecular diodes, the Yale group quickly moved on to more complex devices, namely, switches. A controllable switch of some kind is a minimum requirement for a general-purpose computer. Even more desirable is a switch that can amplify a current, besides merely turning it on and off. Such amplification is necessary to connect vast numbers of the switches, as is required to build complex logic circuits. The silicon transistor fulfills both those requirements, which is why it is one of the great success stories of the 20th century.

The molecular equivalent of a transistor that can both switch and amplify current is yet to be discovered. But researchers have taken the first steps along the path by constructing switches, such as the twisting switch described earlier. In fact, Jia Chen, a graduate student in Reed's Yale group, observed impressive switching characteristics, such as an on/off ratio greater than 1,000, as measured by the current flow in the two different states. For comparison, the analogous device in the solid-state world, called a resonant tunneling diode, has an on/off ratio of around 100.

Similar behavior was observed in the U.C.L.A./HP experiments. In their demonstration, they showed that the conductivity of a molecular layer of rotaxanes, molecules that resemble a core with a surrounding barbell, could be predictably interrupted when a high voltage was applied to a junction containing the molecules. At this voltage, the molecules reacted and changed configuration, altering the lineup of orbitals and interrupting the flow of current through the molecule. Combining a series of these junctions, they built a device that performed a simple logic function.

Perhaps most encouragingly, molecular devices have already proved themselves as memory elements. Besides active, transistorlike devices, memory is the other main requirement for a useful, general-purpose computer. Recall our twisting switch. We altered the internal electrically active unit (the lopsided center benzene ring with opposing NO_2 and NH_2 groups) by keeping just the "electron-sucking" nitro group, NO_2. The change made the molecular orbitals susceptible to becoming modified—either spread out or localized depending on the charge state of the internal group. Absence or presence of charge in the internal node would modify the conduction of electrons through the molecule. By storing charge on the nitro group, we blocked the conduction, which represents a binary "0." Conversely, with no charge stored on the group, the conduction was high, representing a binary "1." Significantly, the molecular memory cell retained (or "remembered," if you will) the stored bit for nearly 10 minutes—an astounding amount of time in comparison with an ordinary silicon dynamic random-access memory (DRAM) element, which can hang on to a bit for only a few milliseconds (silicon DRAMs must be frequently refreshed by an external circuit to retain their data). The construction of the memory element, which involved a relatively straightforward modification to the twisting switch, also demonstrated the ease and flexibility in which molecular-scale devices can be redesigned.

Given the enormous potential advantages of molecular devices, why don't we scrap silicon research and proceed wholeheartedly to molecular-based systems? Because despite the recent auspicious advances, a number of significant obstacles, some fundamental, still stand in the way of fabulously complex and powerful circuits.

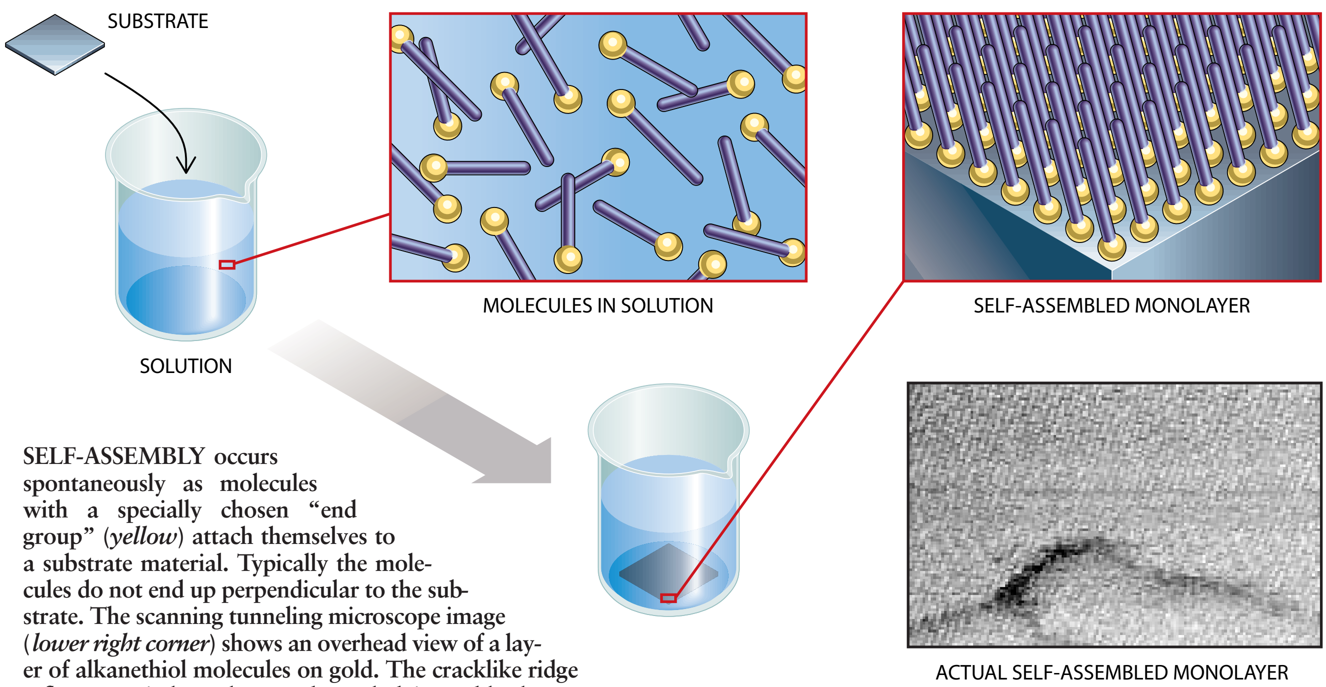
Needed: The Next Transistor

Foremost among them is the challenge of making a molecular device that operates analogously to a transistor. A transistor has three terminals, one of which controls the current flow between the other two. Effective though it was, our twisting switch had only two terminals, with the current flow controlled by an electrical field. In a field-effect transistor, the type in an integrated circuit, the current is also controlled by an electrical field. But the field is set up when a voltage is applied to the third terminal [*see illustration on opposite page*].

A three-terminal molecular device will make possible the chemical synthesis of tremendously efficient and complex circuits. Even before then, combinations of molecular systems with conventional electronics will probably be used in places where the advantages of self-assembly are natural. But interfacing between the molecular and microelectronic worlds will present its own challenges. Computer chips today have two levels of size scale. From the macroscopic level of the chip we can see and hold in our hand, there is a factor of 1,000 in size reduction to get to the gross wiring level, encompassing the largest connections on the chip, which are smaller than a human hair. Then another factor-of-1,000 reduction is necessary to get to the level of the smallest connections and components of the transistors. If molecular devices are to be added to a chip, they will represent yet another factor-of-1,000 reduction in scale down from the smallest microelectronic device components.

Thermal challenges are also staggering, especially if engineers wind up with no alternatives to using molecular devices in modes and configurations similar to those used now with transistors in conventional chips. At present, a state-of-the-art microprocessor with 10 million transistors and a clock cycle of half a gigahertz (half a billion cycles per second) emits almost 100 watts—greater in radiant heat than a range-top cooking surface in the home. Such a unit is close to the thermal limitation of semiconductor technology. Knowing the minimum amount of heat that a single molecular device emits would help put a limit on the number of devices we could put on a chip or substrate of some kind.

This fundamental limit of a molecule, operating at room temperature and at today's speeds, is about 50 picowatts (50 millionths of a millionth of a watt). That figure suggests an upper limit to the number of molecular devices we can closely aggregate: it is roughly 100,000 times more that what we can now do



SELF-ASSEMBLY occurs spontaneously as molecules with a specially chosen "end group" (*yellow*) attach themselves to a substrate material. Typically the molecules do not end up perpendicular to the substrate. The scanning tunneling microscope image (*lower right corner*) shows an overhead view of a layer of alkanethiol molecules on gold. The cracklike ridge reflects a grain boundary on the underlying gold substrate.

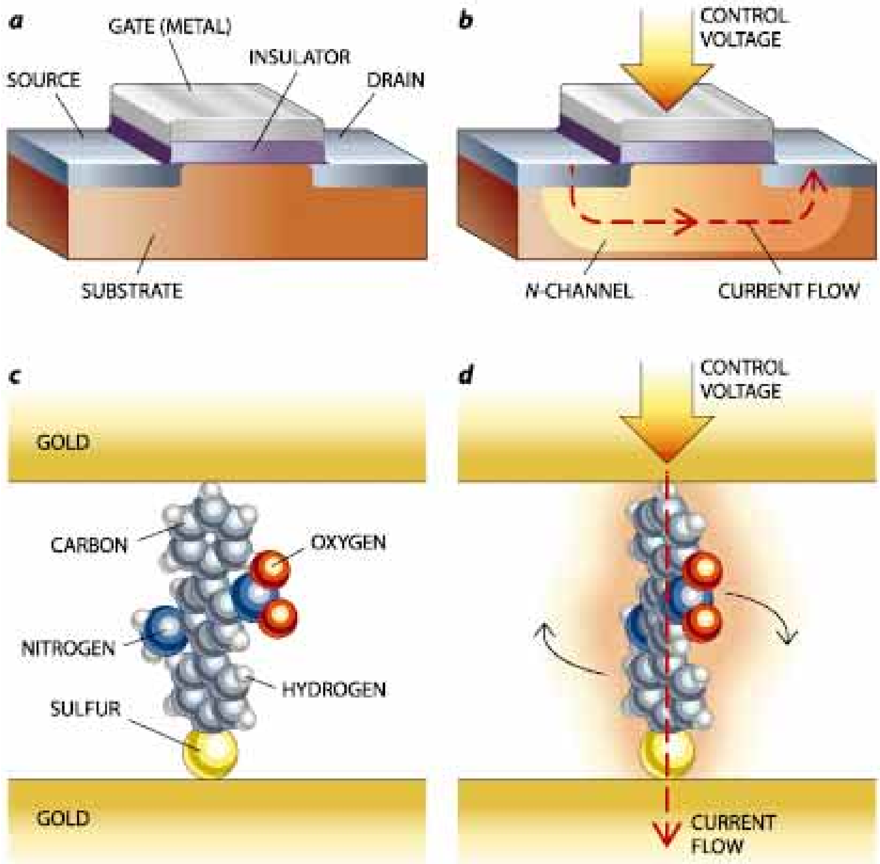
JARED SCHNEIDMAN DESIGN (*illustrations*); PAUL S. WEISS *Pennsylvania State University* (*micrograph*) with silicon microtransistors on a chip. Although that may seem like a vast improvement, it is still far below the density that would be possible if we did not have to worry about heat.

For these calculations, we followed the convention in silicon microelectronics that every device is addressable—or, put another way, that any device can be picked out from among the countless millions through the interconnections, like a house with a unique street address. This kind of addressing (which is called random access) would be required, for example, to retrieve the contents of a particular memory location.

Right now no one knows how to create such an interconnect structure on the molecular level. Straightforward extensions of the present techniques we employ to fabricate complex microelectronics are not practical for molecular-scale electronics, because the lithography needed for creating the interconnections to single molecules is far beyond the capability of known technologies. Is the ability to address every device, the common architecture we use today, necessary or efficient at molecular-scale densities? What will large-scale circuits of this technology look like? Can we use nanotubes, single-walled structures of carbon with diameters of one or two nanometers and lengths of less than a micron, as the next generation of interconnects between molecular-scale devices?

Decades from now, radical departures from present computing design will probably be needed to exploit molecular computing systems fully if we are to extend electronics significantly beyond Moore's Law. We have only very limited ideas about what these departures might be. The ability to construct complex molecular devices, with new paradigms and lists of rules about connecting the various devices, will open up an entirely different way to think about computer design.

Although such departures are fraught with problems, we have no alternative but to solve them if electronics is to continue advancing at something like its current pace well into the next century. And difficult though the challenges may be, the rewards for those who solve the problems could be staggering. By pushing Moore's Law past the limits of the tremendously powerful technology we already have, these researchers will take electronics into vast, uncharted terrain. If we can get to that region, we will almost certainly find some wondrous things—maybe even the circuitry that will give rise to our intellectual successor. SA



CONVENTIONAL MICROTRANSISTOR (*a*) has three terminals, known as the source, gate and drain. A positive voltage applied to the gate draws electrons to the insulator (*b*), enabling current to flow from the source to the drain. A molecule based on three benzene rings (*c*) was also used to switch an electric current. The center ring had asymmetric fragments, enabling it to be twisted by an electrical field (*d*). With a specific voltage applied, the electrical field twisted the molecule and permitted current to flow.

JARED SCHNEIDMAN DESIGN

The Authors

MARK A. REED and JAMES M. TOUR began collaborating on molecular electronics research in 1990. Reed is chairman of the department of electrical engineering and the Harold Hodgkinson Professor of Engineering and Applied Science at Yale University. His research interests include nanotechnology and the fundamental limits of electronic conduction. A former research scientist at Texas Instruments, he recently founded with Tour the Molecular Electronics Corporation in Chicago with the aim of making molecular electronics commercially viable. He is author of over 100 publications and holds 17 patents on quantum effect, heterojunction and molecular devices. Tour is a synthetic organic chemist who has been designing and synthesizing molecules for molecular electronics for 10 years. He is with the department of chemistry and the Center for Nanoscale Science and Technology at Rice University, where he pursues chemical aspects of molecular electronics. Previously, he was at the University of South Carolina, where he spent 11 years on the faculty of the department of chemistry.

Further Reading

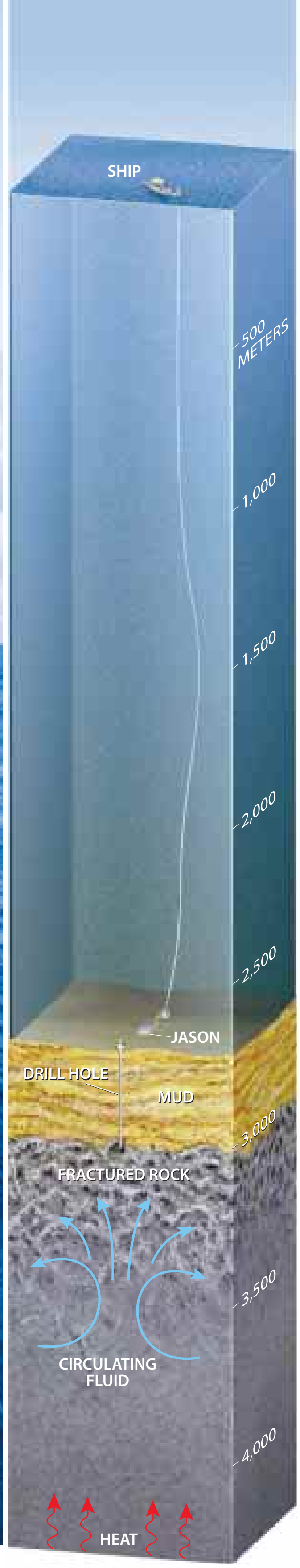
CONDUCTANCE OF A MOLECULAR JUNCTION. M. A. Reed, C. Zhou, C. J. Muller, T. P. Burgin and J. M. Tour in *Science*, Vol. 278, pages 252–254; October 10, 1997.

A DEFECT-TOLERANT COMPUTER ARCHITECTURE: OPPORTUNITIES FOR NANOTECHNOLOGY. J. R. Heath, P. J. Kuekes, G. S. Snider and R. S. Williams in *Science*, Vol. 280, pages 1716–1721; June 12, 1998.

MOLECULAR ELECTRONICS: SCIENCE AND TECHNOLOGY. Edited by A. Aviram and M. Ratner. *Annals of the New York Academy of Sciences*, Vol. 852; 1998.

Two scientists have a hunch that the largest repository of life is not the oceans but the fractured rock beneath them. Staff writer Sarah Simpson recounts their voyage to find proof

Looking for Life Below



Paul Johnson squints at a video monitor that's glowing with a live image of the barren seafloor nearly three kilometers beneath the white caps of the North Pacific. The monitor is his porthole through the single eye of Jason, a submersible robot hovering at the end of an electrical and fiber-optic tether that dangles from the research vessel *Thomas G. Thompson*.

Arms folded across his chest, Johnson glances at the engineer who pilots the robot from his seat in the shipboard control room. The crew has been mentally puttering about the ocean bottom for 13 hours straight, but Johnson doesn't want to miss the task ahead. They have only 30 minutes to snake the six-foot hose of a pump into an opening in the seafloor before an automatic timer switches the pump on. In the dim video image, Johnson sees the water above the hole shimmering with heat. This water is rising from the rocks *underneath* the ocean, and Johnson believes that something in the water is alive—or once was.

The pilot takes a breath and a sip of coffee, then twists a joystick on the panel of gadgets before him. The robot extends its single aluminum arm and four-fingered claw toward the bare hose, which is hardly thicker than the robot's half-inch-wide finger. Grabbing the hose is easier said than done, because using the robot handicaps the pilot in several ways: It offers him no depth perception to gauge distance and no sense of touch to check his grip. To glance left or right, he must push buttons that tilt the camera. Every move happens in slow motion. From the shadows, Johnson and a band of observers grimace when the white hose slithers out of reach. "It's like watching a video game when the other kid won't let you play," Johnson says. Time ticks forward as the pilot flies the robot closer to the evasive hose—and the shimmering water.

Finding microscopic creatures rising

SUBMERSIBLE ROBOT tethered to a ship helps scientists pursue microscopic creatures that may live in fluid-filled cracks within the ocean's rocky foundation.

DAVID FIERSTEIN (*illustration*)

the Bottom

Photographs by Paul Souders

from a seafloor hot spring wouldn't surprise anyone if that spring were a so-called black smoker. Isolated from the sun's life-giving energy, those towering rock chimneys spew scalding fountains of chemicals that give rise to entire food chains of creatures, from sulfur-eating bacteria on up to red-tipped tube worms and predatory spider crabs. Black smokers are fascinating but rare. All of those explored so far add up to no more than a few acres of seafloor.

This warm spring is different: it emanates from a manmade hole, and it is 100 kilometers from the nearest-known black smoker. Johnson and fellow marine scientist Jim Cowen suspect that if suboceanic life is gushing out here, then an inconspicuous Eden of immense proportions very likely dwells inside the fractured rock that underlies all the oceans. This subsurface realm could sustain more living stuff than all marine habitats combined.

It is difficult to resist pondering the global implications of such a discovery. Fed by minerals from within and warmed by magma from below, were fledgling life-forms hiding in the ocean crust while the young Earth endured asteroid assaults and global deep freezes? And if life thrives within Earth's rocky foundation, then why not under the oceans of Jupiter's ice-covered moon Europa or in the riverbeds of ancient Mars?

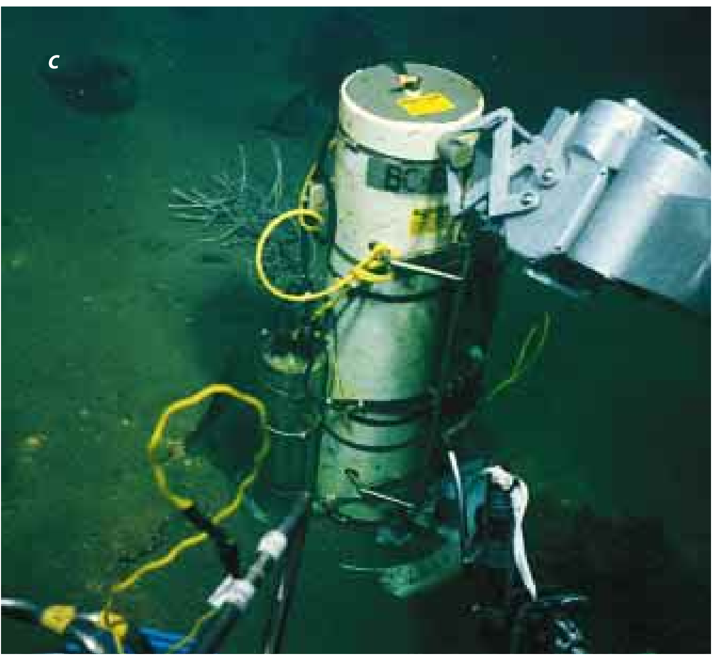
Only 11 minutes now remain on the pump timer. Johnson knows that the pump is the quickest and cleanest way to capture signs of life from the crust. If it clicks on in normal seawater, the sample will be worthless. The robot finally grasps the hose firmly, but the pilot struggles to maneuver the hose into the hole. He just misses, and the audience gasps. At last, the hose enters the shimmering water with a minute to spare.

Tense and frustrating to watch, this operation is not so different from what it might be like to conduct a robotic search for life on Europa or Mars. But whether in space or at sea, small victories sometimes create unexpected problems, as the scientists on board the *Thompson* are soon reminded. Squeezing the hose for three hours overheats Jason's fingers, and the crippled robot must temporarily cease its work.

Indeed, frustration at sea was what first drew Johnson and Cowen together, in 1994. That fall the two scientists, then acquaintances conducting unrelated research, ended up on the same ship. "We had crummy weather, we had equipment failures, we had operator errors—we had a lot of spare time," Johnson remembers. "So Jim and I started talking." They soon discovered that they shared a controversial idea—that life might flourish in the ocean under the seafloor—and thought they saw a way to test it. Their peers reacted skeptically, but after Johnson and Cowen twice revised their approach, the National Science Foundation came through with $1.6 million.

But a single research program might not be enough. Even if the microbial wonderland that they hypothesize does exist, it may take decades to prove it. In most places the crust lies beneath a few kilometers of seawater—not to mention a mound of muck deep enough to bury a 60-story skyscraper. The two scientists knew that the best chance to prove their theory was to find spots in the seafloor where heat from below forces water out of the rock.

On their first voyage, in 1997, they located a few eligible leaks. A year later they capped these leaks with sophisticated



PILOT DIRECTS THE ROBOT, Jason, from a control room (*a*) on board the *Thomas G. Thompson* (*b*). He uses the robot's single claw to grab one of six plastic columns that have been sitting on the bottom of the North Pacific for a year (*c*). The team works night and day to collect the columns, which house filters designed to trap signs of life that may be squirting out of the rocky crust. The engineers reel Jason back on deck only to change locations or to make repairs (*d*).

filters designed to snare cells, DNA or other signs of life that are flushed out with the water. In late August 1999 they set sail once more. On this 13-day expedition, they need Jason and its nine-man crew from the Woods Hole Oceanographic Institution in Massachusetts to retrieve the six filters they planted on the seafloor in 1998. They also want to test a new pump and a smaller, cleaner filter that Cowen's team designed to stay down for only a week.

Departing from its home port at the University of Washington in Seattle, the *Thompson* followed a westerly course toward a jagged gash in the seafloor called the Juan de Fuca Ridge, which mirrors the coastline some 350 kilometers from land. Part of a worldwide web of lava-belching cracks, the ridge is forested with black smokers, appropriately named: Godzilla, Inferno, Hulk. But Johnson and Cowen are not investigating those hot spots. The *Thompson* instead stopped 100 kilometers short of the ridge, above the relatively uncharted Cascadia Basin, a low spot between the coast and the ridge. Unwinding a giant spool of steel-armored cable, the Woods Hole engineers slowly lowered Jason toward an ordinary patch of cold seabed, where molten lava stiffened into rock called basalt more than three million years ago. Cold rock hardly seems a tantalizing haven for throngs of microscopic life, but Johnson and Cowen see things differently.

For one thing, the old crust isn't as solid as you might think. Johnson, a 59-year-old geophysicist from the University of Washington, has spent much of his career getting to know ocean basalt. By studying minuscule variations in the gravitational field of the seafloor, he has estimated that up to 20 percent of the top 600 meters of the rock in this area is composed of water-filled voids. "Every single place where there's water, space and temperatures below 100 degrees Celsius, you've got life," Johnson states, reciting the mantra of his fellow believers. (Then again, this confidence comes from a man who told a student in 1967 that plate tectonics is a ridiculous idea. "So I have a long tradition of being absolutely wrong," he jokes.)

Certainly many biologists will think that Johnson is absolutely wrong about suboceanic life, too, unless he and Cowen collect irrefutable evidence. Their biggest challenge is to capture unique life from below without allowing any common life from above to sneak into the samples. That may sound like a simple task, but microbes are notoriously opportunistic. They can scrape together a living from simple molecules of carbon, sulfur and iron, which are found almost everywhere: in seawater, in mud overlying the rocks—even on the metallic surfaces of scientific devices. Accessing the deep crust with a drill only magnifies the risk of contamination. Like pulling a stopper in a bathtub, punching a hole in the

HAULING THE FIRST COLUMN on deck, biologist Jim Cowen (*far left*) and another scientist warily avoid the poison that kept unwanted creatures from nesting in the filter. The next day geophysicist Paul Johnson (*bottom left*) helps an engineer remove Jason's single arm, which malfunctioned before any other columns could be retrieved. Painstaking repairs (*right*) halt the team's progress for more than 24 hours.

ocean bottom usually allows the life-infested ocean to rush in.

Not so with the hole now framed in Jason's video camera. There warm water flows from the top of a steel straw that extends through 250 meters of mud and penetrates 50 meters into the rock below [*see illustration on page 95*]. Pressure has been driving water out of that hole since it was drilled three years ago and, perhaps, has flushed out contamination. When Cowen first heard about this drill hole, the 48-year-old biologist says he felt "like a candy-crazed kid being given the keys to a candy store." He and his group from the University of Hawaii are attempting to gather suboceanic life inside a four-foot section of plumbing pipe connected to the steel straw. Inside the plastic column is a filter that has been scavenging signs of life from the warm water flowing through it for the past year. Or so they hope.

The Jason pilot maneuvers the robot for a closer look at a small titanium cylinder riding piggyback on the scavenging column. The cylinder is loaded with electronic sensors that measure water temperature and flow rates, which help Johnson and his students to see whether the conditions could possibly support life. A scientist frowns as he notices the green fuzz of corrosion around brass connectors in the titanium lid—so much corrosion that he wonders if the device will make it to the surface without leaking. High-pressure leaks could trigger an explosion at the surface. Even a small blast would be bad, because the scavenging column contains mercuric chloride, a deadly poison that the biologists use to kill the crustal critters trapped in the filter and to keep the seawater bugs away.

"The poison was meant to percolate through slowly to kill things over time," Cowen explains as the team transfers the scavenging column from the seafloor to the ship's deck for a cleansing shower. "I think it's long gone." Back in the biology laboratory, he and his students break into the column with no problems. Cowen changes his blue surgical gloves, careful to be clean before reaching inside for the filter. Delicately but briskly, he pulls out the folded layers of woven glass fibers, now saturated with greenish-brown slime. "These were pristine white when we put them in here," he comments. A smile spreads over his face as he and his students divvy segments of the filter into protective glass tubes.

The green slime is just what they had hoped to find. They collected a similar but smaller sample here last year and gave it to Steve Giovannoni, a molecular biologist at Oregon State University known for his expertise in deciphering the genetic code of seawater microbes. "We know what's in seawater, and this stuff looks different," Giovannoni told them before they left. But "different" isn't proof that the bugs came from the crust. Cowen knows that the more organic debris they collect, the better their chances to rule out contamination. That's why they want to send down the new pump and filter before they move to the next site.

Four days into the cruise the problem that began with Jason's overheated claw mushrooms into a crisis that halts the team's ambitious agenda. "There's no joy in Mudville today," Johnson remarks as he paces among the cranes, winch and unused buoys crowding the ship's aft deck. A dozen albatross gather off the stern. Nature is siding with science on this calm, sun-drenched afternoon, but the machines are not. Once again the engineers are reeling Jason back to the ship. The robot had nearly reached the bottom when they discovered that its claw, supposedly repaired, was still paralyzed.

The deep ocean crust could harbor more life than all marine habitats combined.

Johnson, who has lived some two years of his life at sea, expects this kind of trouble in deep-ocean research. "At least half of what goes on are disasters," he says. Yet he claims to never grow weary. His childhood dream was to go to the moon, but polio left him with a limp. "So," he explains, "I went the other way." That decision took place a quarter of a century ago. Veterans like Johnson know that their most agonizing moments at sea will be selecting which carefully planned activities to abandon. They intentionally overbook each expedition so as not to waste precious ship time, which costs about $20,000 per day.

By sunset the engineers have amputated Jason's malfunctioning arm. A black trash bag protects the vulnerable stump from salt spray, and the mineral oil that keeps the robot's insides from imploding at depth dribbles from a Plexiglas chamber. Inside the workshop one engineer rebuilds the claw while two others rewire the electronics. As always, the team works through the night, but it fails to diagnose Jason's affliction.

Johnson and the other leaders decide to reshuffle the cruise timetable to give the Jason crew more time. Two days ahead of schedule the captain plots a course to Axial volcano, a blister of young crust along the ridge. There they expect to find a more diverse and populous neighborhood of microbes, which will help them imagine the subsea milieus that must exist between here and there. At lunch the next day someone asks Johnson what he plans to do when they arrive. "If the arm is working, we'll dive and do a lot of things; if the arm isn't working, we'll dive and do a great deal less," Johnson replies in his typical even-keeled manner. The truth is, without Jason's arm they have no hope of retrieving the five scavenging columns still sitting on the seafloor.

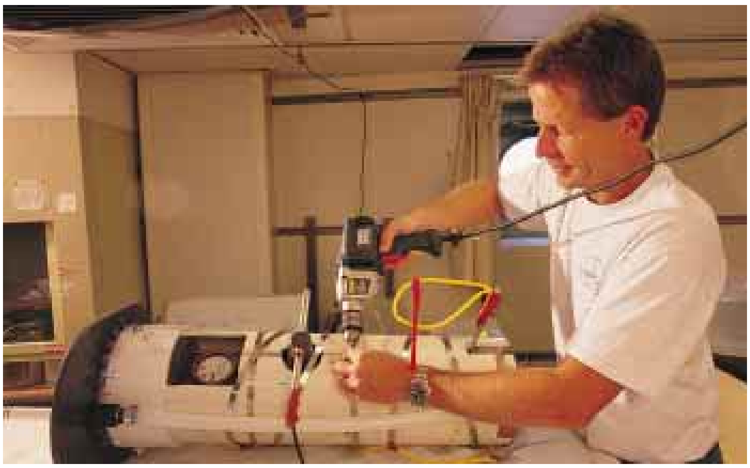
The 12-hour journey to Axial gives the engineers the time they need. As soon as the *Thompson* reaches the underwater volcano, the sub descends within a few meters of pillowlike mounds of glassy basalt, evidence of molten rock solidifying on contact with frigid seawater. Through white webs of bacteria, floating like sheets of disintegrating tissue paper, the scientists spot a column perched on the platform that they had cemented to the bare rock last year.

They haul the column on board, and Johnson checks the water-flow sensor. He is fascinated by an intriguing pattern: the volume of water coming out of the seabed fluctuates in sync with the passing tides. It is well known that the ocean over the Juan de Fuca ridge changes depth by two or three meters with each tidal cycle. What Johnson has discovered is that the weight of the passing tidal bulge compresses the rock, which expands again when the tidal bulge moves on. Heat alone moves water through the rock at the rate of only a few meters per year. "That's really slow," Johnson points out. "But if you take that same environment and squeeze it every 12 hours, then you've got velocities on the order of meters per *day*." Microbes living in the rock, which crave chemical nutrients dissolved in the circulating water, couldn't ask for a quicker and more reliable delivery service.

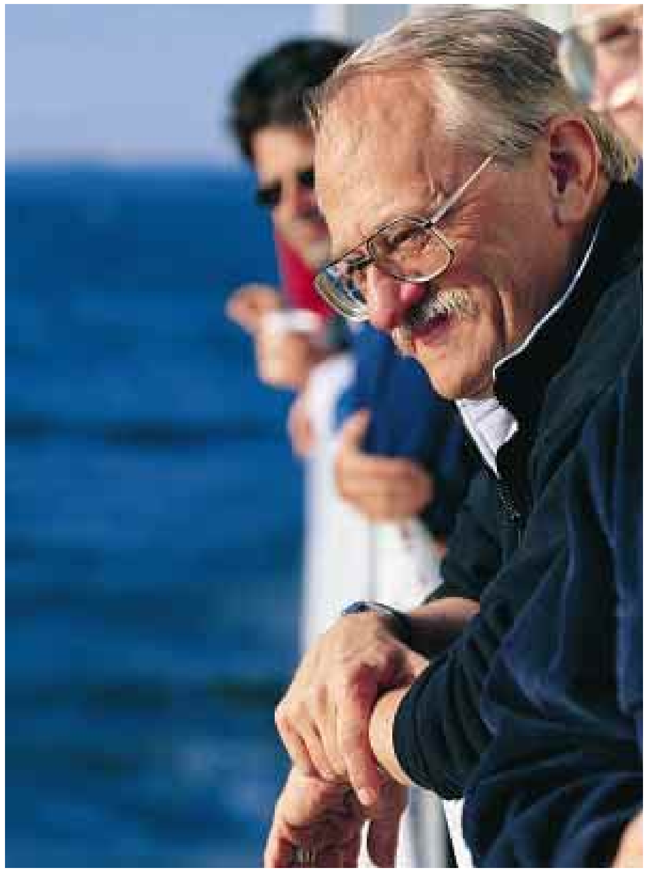
The team picks up a third column, also in young crust, then turns back toward the Cascadia Basin. The *Thompson* arrives at the drill hole with only a day to spare before it must return to shore. Early that afternoon Jason grabs the small column they put down a week ago, and Cowen's crew hauls it to the lab to see what is stuck in its newfangled filter. The ship has already begun to move six kilometers south to an elevated spot of crust that barely protrudes above the muck. There, where warm water rises in hot curtains from a maze of cracks in the rock, await the last three scavenging columns left behind when the ship departed early for Axial.

Cowen snaps on a fresh pair of blue gloves and loads swing music into the lab stereo. Jason has been performing without a hiccup since the dives at Axial. Best of all, the team has accomplished most of its highest priorities—at this point, it has recovered half of the scavenging columns, all of which performed as planned during an entire year on the ocean bottom. The final tasks are all but complete: Jason has just packed two of the remaining columns in a buoyant basket and is ascending with the third hooked to its frame.

The buzz of the drill Cowen uses to open up the small column drowns out the brassy blare of the horns and the beat of the drums. He beams as he pulls out the round, sandwichlike filter, now clogged with the familiar green ooze. "This is as clean as it



COWEN OPENS A COLUMN (*left*), and he and his students discover that its filter is clogged with green slime—and possible signs of life from the crust.



BUOYANT BASKET carries the last two columns to the surface, but rough waves dump them back into the ocean despite the best efforts of the crew (*above*). And yet, as the *Thompson* pulls into port the next morning, Johnson (*right*) maintains that the trip's successes greatly outweighed its disappointments.

gets," Cowen notes as he slices the filter like a miniature pie.

Johnson enters the room, looking serious. The basket seems to be holding the last two columns hostage on the seafloor. It is not responding to commands to drop its weights, and the crew worries it won't surface before nightfall, only five hours away. (In an arrangement similar to that of a hot-air balloon, aluminum bars connect the basket to a team of floats, which are impossible to spot in the dark despite their bright-yellow color.) The task can't wait until morning, because the barometer is dropping and the waves are mounting after a two-week calm. In a brief but intense discussion, Johnson, Cowen, the ship's captain and the Jason crew leader decide to send the robot down to release the weights. During the three hours it takes for the basket to surface, the weather deteriorates.

The swells are now surging to nine feet. Johnson stands at the rail wearing a hard hat, life vest and rubber gloves—he has volunteered to close the safety valves on the columns' poison boxes before the crew brings the basket on deck. The captain nudges the heaving, 3,200-ton bulk of the *Thompson* within spitting distance of the bobbing yellow floats. Stretching over the rail and flailing with a metal hook in hand, the chief mate snags a rope tied to the basket's frame and hooks it to a crane. Now lifted just above the water, the floats can no longer hold the basket upright, and an ominous gray swell tilts it sideways.

Johnson sees that one of the two scavenging columns was loaded heavy-side-up and now protrudes precariously. The crane operator throws the winch to full power as the passing wave allows the basket to hang free for an instant. The next swell again flips it on its side, and the inverted column teeters on the container's edge. A third swell engulfs the basket, and after the longest second of the cruise, it pops above the spray with *neither* column inside. Johnson lunges to the railing to watch both instruments sink slowly out of sight.

Losing $25,000 in equipment is bad, but losing the year's worth of clues caught in the two filters is unthinkably upsetting. The chief mate launches into apologies, but Johnson assures him that none are necessary. He turns toward the crowd lining the rail of the deck above him—a collage of faces looking as stunned as he feels. Cowen is among them, but the two scientists don't bother speaking until later that evening, when the ship is headed to port. "There was no villainy, no incompetence," Johnson will later say, "just the wrong wave at the wrong time." They can only hope that the filters they did retrieve hold the answers they are looking for. At this point, they have no money to come back and try again.

Several months later Cowen receives an e-mail report from an organic chemist in Chicago who has been studying some of the samples from the Cascadia Basin. It turns out that the water the team collected at the drill hole contains fatty cell fragments, called lipids, of a kind that doesn't show up in the mud or seawater samples from the same site. Giovannoni has other exciting news: he has discovered in the once shimmering water a diverse array of microbes, among them heat-loving bacteria that could never survive the icy temperatures of the ocean bottom and anaerobic bacteria that would choke on the oxygen present in normal seawater. "The names tell the story," Giovannoni says. "Show this list to any microbiologists, and they'd say it was a jackpot." But this jackpot is still short of proof that the bugs came from the crust. The same slew of microbes could also live happily in other warm, oxygen-deprived locales—namely, the steel pipe that lines the drill hole.

Many more months of arduous laboratory analyses may turn up something more definitive. In the meantime, Johnson and some of his colleagues are asking the National Science Foundation to finance a return trip to the site of the lost columns. His new team wants to drive a 10-foot titanium pipe into the bare rock to serve as a permanent spigot for tapping fluids—and a potential multitude of microscopic creatures—in the crust. "Our titanium hypodermic needle would be giving Mother Earth a type of blood test," Johnson says. "Only in this case, we would be quite pleased if she came up 'infected.' " SA

ASTRONAUTICS_SPACE SUIT

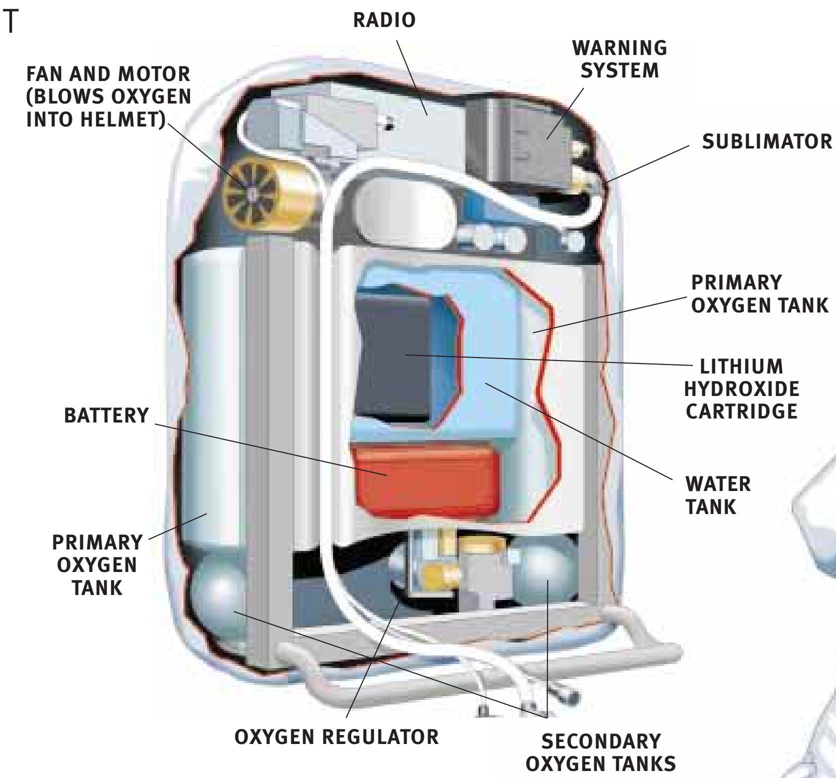
A Spaceship for One

If spacewalkers seem so serene floating 500 kilometers above the earth, it is a testament to how effectively cocooned they are in their $12-million space suits. Those suits are the only thing that separates astronauts from one of the harshest-known natural environments. Like a tiny spaceship, the suit provides oxygen, communications and protection from temperature extremes, cosmic and ultraviolet radiation, and micrometeoroids.

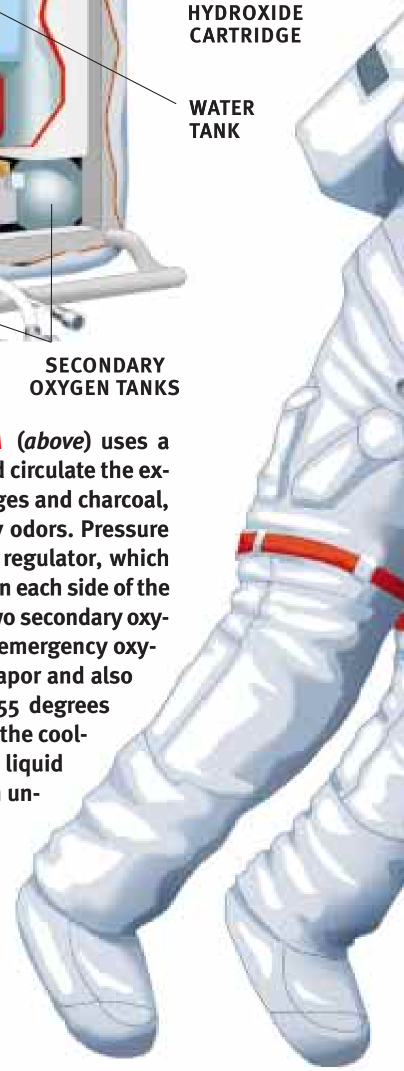
The "primary life-support system," worn on the back, contains the heart of the atmospheric system. It recirculates the user's exhalations, removing carbon dioxide and adding oxygen as needed. The standard environment in the suit is just 0.29 atmosphere of pure oxygen; this reduced pressure serves two purposes. First, it considerably improves freedom of movement for the wearer in the near vacuum of space. Second, it decreases the overall stress on the suit. Because of the low pressure, however, astronauts must "prebreathe" pure oxygen before donning the suit. This prebreathing reduces the amount of nitrogen dissolved in their tissues and enables them to avoid a case of the bends as they go from the shuttle to the lower-pressure environment inside the suit.

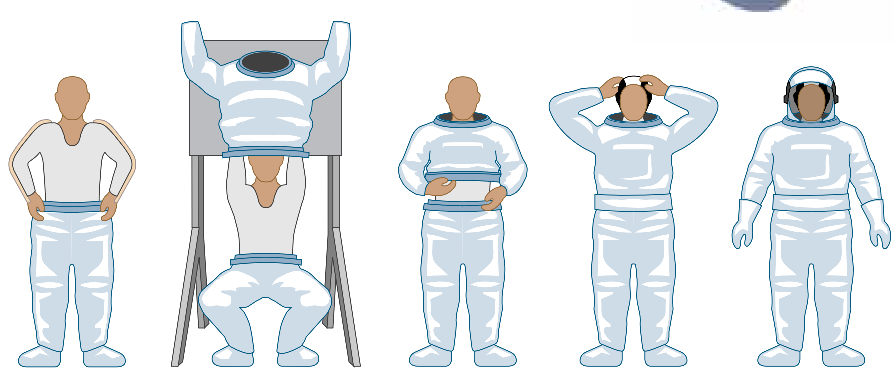
A 32-ounce drink bag in the upper torso enables astronauts to imbibe through a mouthpiece in the helmet. Of course, that means there has to be a provision for urine collection (and there is: it's a modified adult diaper). The suits, officially known as extravehicular mobility units, are built under the supervision of prime contractor Hamilton Sundstrand with contributions from 52 other companies.

—Glenn Zorpette, staff writer



PRIMARY LIFE-SUPPORT SYSTEM (*above*) uses a fan to blow oxygen into the helmet and circulate the exhalations to lithium hydroxide cartridges and charcoal, which remove carbon dioxide and any odors. Pressure reductions are sensed by the oxygen regulator, which adds oxygen as necessary from tanks on each side of the pack to keep the pressure constant. (Two secondary oxygen tanks can provide half an hour of emergency oxygen.) The sublimator removes water vapor and also cools the air to 13 degrees Celsius (55 degrees Fahrenheit). It also removes heat from the coolant water that circulates through the liquid cooling and ventilation garment, worn under the suit.

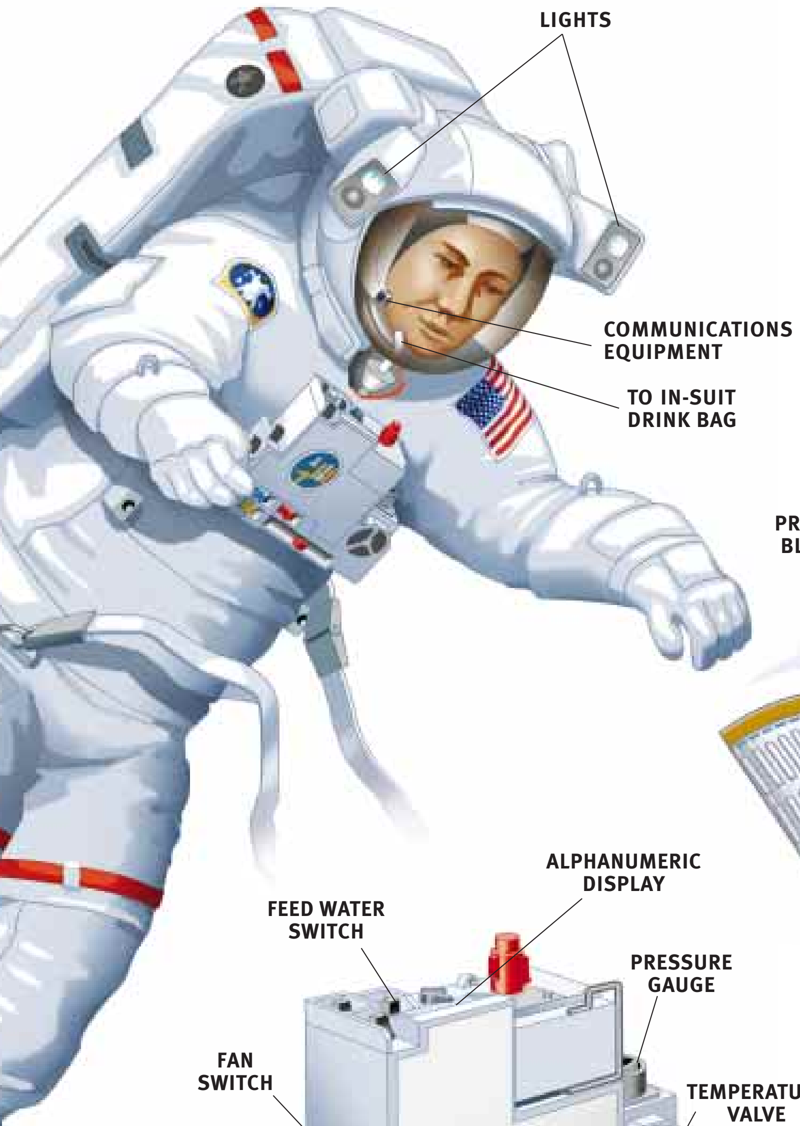




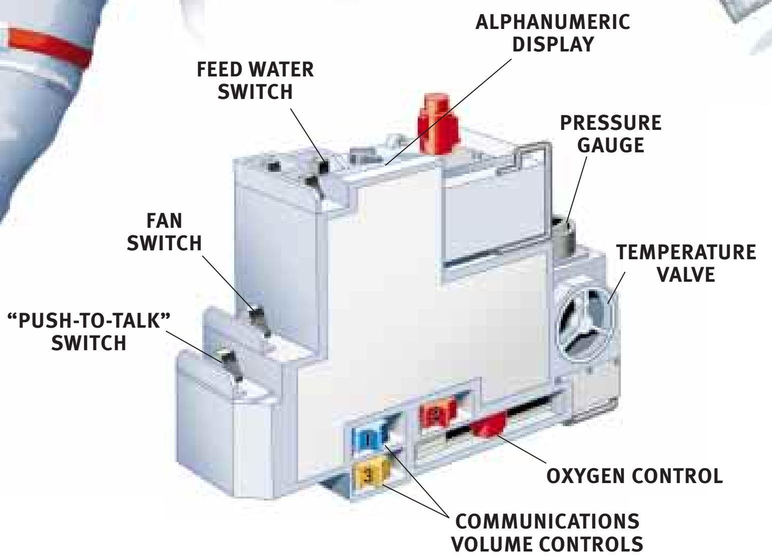
DONNING PROCEDURE begins with the pants ("lower-torso assembly") with the boots attached. Then the astronaut pushes upward into the "hard upper torso," which is held by a rack. Once in the upper garment, the lower piece is pulled up and joined to the upper. Next, the black-and-white "Snoopy" head cap goes on; it contains the headphones and microphone for communications. Then come the gloves and, finally, the helmet.

Working Knowledge

LIQUID COOLING AND VENTILATION GARMENT (*left*) is like a tricot-and-spandex union suit. Its main function is keeping the astronaut comfortable in an environment in which temperatures can range from 120 degrees C (250 degrees F) in direct sunlight to –150 degrees C (about –250 degrees F) in the shade. Some 90 meters of plastic tubing run through the suit; water flowing in this tubing is cooled by the sublimator as necessary to keep the astronaut comfortable.



SPACE SUIT MATERIAL (*left*) has an inner pressure bladder made of urethane-coated nylon, restrained by a Dacron cover, to keep the oxygen inside the suit. Outer layers, which keep in heat and protect against micrometeoroids, include several of aluminized Mylar, for thermal insulation, and an outer cover of Teflon, Kevlar and Nomex.



DISPLAY AND CONTROLS MODULE (*above*) lets astronauts alter the flow rate of the water coolant in the suit and control the communications systems, fans and breathing mode of the oxygen regulators. This module also connects to a warning system in the life-support backpack, allowing the astronaut to run a diagnostic program to check various subsystems. The results of the diagnostics are displayed on the module's main alphanumeric display. A separate analog gauge continuously displays the suit's pressure.

DID YOU KNOW...

- The specified maximum duration for a space walk is seven hours, but generous margins permit longer excursions. The longest extravehicular activity (EVA) by U.S. astronauts took place on May 13, 1992, when crew members Pierre Thuot, Rick Hieb and Tom Akers were outside the shuttle for eight hours and 29 minutes working on an Intelsat communications satellite.
- Before the first scheduled shuttle space walk, on the fifth mission in 1982, the fan in the life-support system of a spacesuit failed, and the excursion had to be canceled. It was the only significant problem with a shuttle suit in orbit.
- Astronauts working on the International Space Station will have an accessory, the Simplified Aid for EVA Rescue (SAFER), to let them propel themselves back to safety if a mishap leaves them adrift. During construction, the shuttle will be docked to the station, making a timely rescue by shuttle more difficult. The device, which uses nitrogen as a propellant, attaches to the bottom of the life-support backpack.

NEXT MONTH: What astronauts wear during launch.

ILLUSTRATIONS BY GEORGE RETSECK

The Amateur Scientist

HEART_BEEP

Home Is Where the ECG Is

Watch your heartbeat with do-it-yourself equipment, as described by **Shawn Carlson**

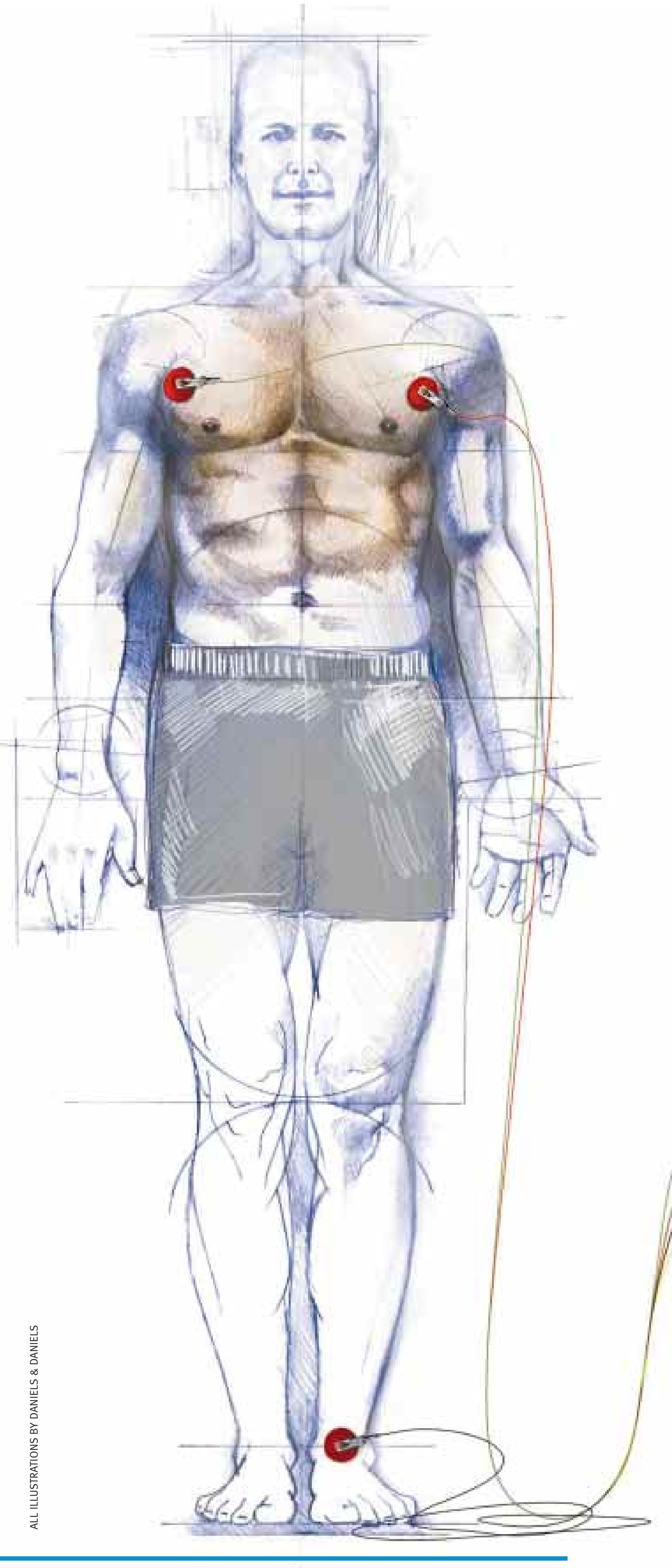
I have never been so terrified as the day I thought I was going to lose my wife. I blew through all the red lights on our way to the hospital, as Michelle rapidly grew weaker in the passenger seat. It all started just 10 minutes earlier when I confirmed with my homemade electronic stethoscope (see the October 1997 column) that her heart was beating abnormally. By the time we barreled into the hospital parking lot, she could hardly speak at all. I had to carry her into the emergency room.

It turned out to be an easily treated side effect of a prescription steroid she was taking. We were home in six hours. But the experience scared me so much that I built Michelle an automated heart-monitoring device to give us more warning should the symptoms ever reappear. That monitor was acoustical. Although such a sensor makes it easy to detect an irregular rhythm, you can learn much more by recording the heart's electrical signature. So I decided to upgrade to an electrocardiograph, or ECG (also abbreviated EKG). It can be built in an afternoon for about $60.

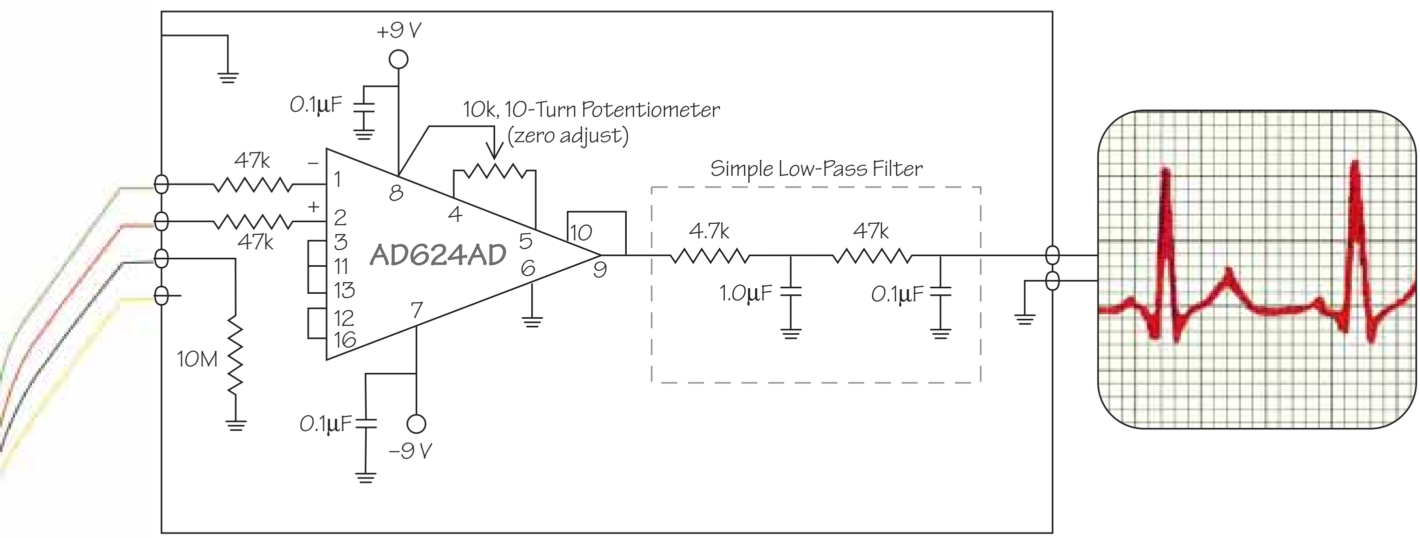
The heart's strong pumping action is driven by powerful waves of electrical activity in which the muscle fibers contract and relax in an orchestrated sequence [see "Surgical Treatment of Cardiac Arrhythmias," by Alden H. Harken; Scientific American, July 1993]. These waves cause weak currents to flow in the body, changing the relative electric potential between different points on the skin by about one millivolt. The signals can change sharply in as little as one fiftieth of a second. So boosting this signal to an easily measured one-volt level requires an amplifier with a gain of about 1,000 and a frequency response of at least 50 hertz.

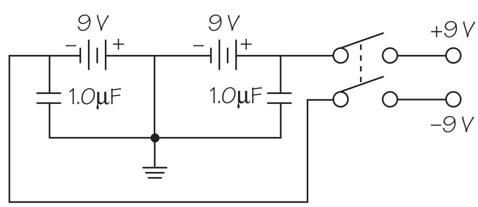
You signal jockeys may be thinking about using an operational amplifier. But two vexing subtleties make most op-amps unsuitable. First, when two electrodes are placed at widely separated locations on the skin, our epidermis acts like a crude battery, generating a continuously shifting potential difference that can exceed two volts. The cardiac signal is puny in comparison. Even worse, your body and the wires in the device make wonderful radio antennas, which readily pick up the 60-hertz hum that emanates from every power cable in your home. This adds a sinusoidal voltage that further swamps the tiny pulses from your heart. And because these oscillations lie so close to the frequency range needed to track your heart's action, this unwanted signal is hard to filter out.

Both problems generate equal swells of voltage at the amplifier's two inputs. Unfortunately, op-amps usually can't reject these signals. If we want to ensure that this "common-mode" garbage (whose amplitude, remember, can be over



ALL ILLUSTRATIONS BY DANIELS & DANIELS





HEART OF THE APPARATUS **is an amplifier and filter circuit, which boosts the feeble voltages measured across different points on the skin. Use of the instrumental amplifier, rather than a standard operational amplifier, ensures a precise voltage difference even if the absolute voltage level fluctuates. The output can be displayed on an oscilloscope or on a home-built monitor.**

1,000 times greater than that of our signal) adds no more than a 1 percent error to our voltage measurement, we need a common-mode rejection ratio (CMRR) of at least 100,000 to one (100 decibels). This precision eludes most op-amps.

When an application calls for both high gain and a CMRR of 80 dB or greater, experienced experimenters often turn to special devices called instrumentation amplifiers. When set to a gain of 1,000, the AD624AD from Analog Devices (www.analog.com) offers CMRRs exceeding 110 dB. It can be purchased on-line from Pioneer Standard Electronics (www.pios.com) for $23.50. Gadgeteers may wish to experiment with less expensive options, such as the AD620AN.

The AD624AD makes it easy to monitor your heart [*see illustration on page 105*]. A gain of 1,000 is selected by shorting certain pins together as shown. The two-stage RC filter weeds out frequencies higher than about 50 hertz. I used a four-wire phone cord to carry the signals between my body and the amplifier. You'll need only three of the wires. The side of my project box sports a phone jack for easy connection and disconnection.

I fashioned my first electrodes out of quarters that had been smeared with a conducting layer of shampoo, taped firmly to my body and connected to wire leads. They worked. Then I discovered that anyone can buy bags of 50 of the real thing: the self-sticking electrodes used by cardiologists. The cost is about $13 on-line from www.medicalbuyer.com (part no. 9641). Just peel and stick. I terminated the signal wires with alligator clips to grip the metal nipples on the backs of the electrodes.

Connect the negative lead to your subject's left wrist, the positive lead to the right wrist and the ground lead to the left shin just above the ankle. It proved a bit cumbersome to operate test equipment with my wrists wired up, so I attached the right and left leads just below my armpits and ran the wires under my clothes and out just above my belt buckle.

The bouncing ECG trace makes a delightful display for any oscilloscope. Oscilloscopes are essential for any electronics hobbyist, so if you don't already own one, you should. Dealers of electronics surplus equipment sell two-channel scopes with sweep speeds of 100 megahertz—far faster than you need for a simple project such as this—for about $250. And you may be able to find even better bargains through on-line auction sites like eBay or at ham radio flea markets, called hamfests, run by local ham clubs. If you're on a tight budget, you could build a cheaper monitor; for suggestions, check out the discussion about this project on the Society for Amateur Scientists's Web site.

If you want to digitize your heart traces for computer analysis, you'll need an analog-to-digital converter that can sample at 100 hertz or better—that is, at least twice the largest signal frequency. Both Vernier Software (www.vernier.com) and National Instruments (www.ni.com) sell such units. Serious amateurs should consider NI's extensive line of software, which offers turnkey solutions to just about every data acquisition and analysis challenge there is. Though pricey, these packages can change your life as an experimenter. SA

For more information about this and other experiments for amateur scientists, check out the Society for Amateur Scientists's Web site at sas.org. As a service to the amateur community, SAS will provide the electronic components only, including the electrodes (but no circuit board or project box), for $60. You can write the society at 4735 Clairemont Square PMB 179, San Diego, CA 92117, or call at 619-239-8807.

LOGIC_PROBLEMS

Paradox Lost

Careful analysis can untangle some logical conundrums, says **Ian Stewart**

Some of the most provocative problems in mathematics concern logical paradoxes. The deepest paradoxes are self-contradictory statements; the best known of these is "This sentence is a lie." To analyze such statements, mathematical logicians have to be very careful in defining their terms. Some paradoxes stand up to strong scrutiny, and when they do, they illuminate the limitations of logical thinking. Other paradoxes don't fare so well under close examination. Here are my views on a few of them, which you may feel free to challenge.

Protagoras was a Greek philosopher who taught law in the 5th century B.C. He had a student who agreed to pay for his law lessons after he had won his first case. But the student didn't get any clients, and eventually Protagoras threatened to sue him. Protagoras reckoned that he would win either way: if the court upheld his case, then the student would be required to pay up, but if Protagoras lost, then by their agreement the student would have to pay anyway because he would have just won his first case. The student argued exactly the other way around: if Protagoras won, then by their agreement the student would not have to pay, but if Protagoras lost, the court would have ruled that the student did not have to pay.

All great fun, but I don't think this one stands up to scrutiny. Both litigants are doing a pick-and-mix—at one moment they assume that their agreement is valid, but then they assume that the court's decision can override it. But why would you take an issue like this to court in the first place? Because the court's job is to resolve any ambiguities in the contract and override it if need be. So if the court rules for Protagoras, the student has to pay up, but if the court sides with the student, he doesn't have to. Under the harsh glare of logic, this paradox seems to melt away, so I call it an example of Paradox Lost.

Let's turn to a much more interesting paradox devised by Jules Antoine Richard, a French logician. In the English language, some phrases define positive integers, and others do not. For example, "The year of the Declaration of Independence" defines the number 1,776, whereas "The historical significance of the Declaration of Independence" does not define a number. Now consider this phrase: "The smallest number that cannot be defined by a phrase in the English language containing fewer than 20 words." Observe that whatever this number may be, we have just defined it using an English phrase containing only 19 words. Oops.

What's going on here? The only obvious way out of the conundrum is if the proposed phrase does not actually define a number. If that were the case, the paradox would disappear because the statement would not contradict itself. So we must determine if this hypothetical number—the smallest that cannot be defined in a short phrase—really exists.

If we accept that the English language contains a finite number of words, then the number of phrases with fewer than 20 words is itself finite. For instance, if we allow 99,999 words, then there are at most $100{,}000^{19}$ phrases of 19 words or fewer. (To include the shorter phrases in the total, we also allow blank words, which explains why the base is 100,000 instead of 99,999.) Of course, many of these phrases make no sense, and many of those that do make sense don't define a positive integer, but that just means we have fewer phrases to consider. Between them, they define a finite set of positive integers, and it is a standard theorem of mathematics that in such circumstances there is a unique smallest positive integer that is not

PROTAGORAS'S PARADOX

PROBLEM:

Protagoras, an ancient Greek philosopher, gives law lessons to a student who agrees to pay after he wins his first case. But the student gets no clients, so Protagoras sues him.

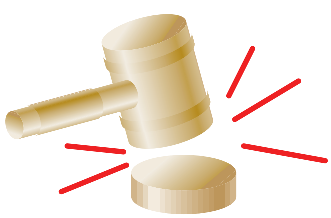
PARADOX:

Protagoras believes he will win either way because:
- If the court sides with him, the student will have to pay.
- If the court sides with the student, the student will have to pay anyway because he will have just won his first case.

The student believes he will win either way because:
- If the court sides with him, he will not have to pay for the lessons.
- If the court sides with Protagoras, he will not have to pay, because he will not yet have won his first case.

RESOLUTION:

The court's purpose is to override contracts if need be. Therefore, the second parts of both Protagoras's and his student's analyses are invalid.

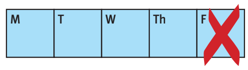


ALL ILLUSTRATIONS BY BRYAN CHRISTIE

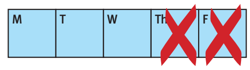
SURPRISE TEST PARADOX

PROBLEM: A teacher tells her students that there will be a surprise test one day next week (Monday through Friday).

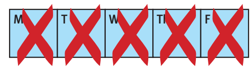
PARADOX:



The students reason that if the test does not take place by Thursday, it must occur on Friday. Therefore, it would not be a surprise test.



Because the surprise test can't happen on Friday, if the test does not take place by Wednesday, it must occur on Thursday. Therefore, it would not be a surprise test.



Using the same argument, the students can also rule out Wednesday, Tuesday and Monday. Therefore, no surprise test is possible.

RESOLUTION:

MONDAY	TUESDAY	WEDNESDAY
Students: "The test will be today."	Students: "The test will be today."	Students: "The test will be today." Teacher: "You're right!"

The students' argument is logically equivalent to the act of announcing every morning, "The test will be today." Because they expect the test to happen on each day, they naturally won't be surprised by it.

in the set. So on the face of it, Richard's 19-word phrase must define a positive integer.

Yet it can't. One could argue that another phrase, "A number that when multiplied by zero gives zero," would let us wriggle off the logical hook because it defines all positive integers, leaving nothing for Richard's phrase to define. But if a phrase is ambiguous, we must rule it out as a definition, because a definition surely requires unambiguity. Is Richard's phrase ambiguous, then? Not really. It defines a number uniquely—there cannot be two distinct smallest numbers that satisfy its conditions. Note that if instead we had considered the phrase "The smallest number that cannot be defined by a phrase in the English language containing fewer than 19 words," we wouldn't have had a problem. So Richard's paradox tells us something quite deep about the limitations of language as a description of arithmetic. Because the problem remains inscrutable even under close examination, I call it an example of Paradox Regained.

In a more recreational vein, there is the Surprise Test paradox. A teacher tells her class that there will be a test one day next week (Monday through Friday) and that it will be a surprise. The teacher can choose any day, and there is no way that the students can predict that day in advance. The students, however, reason like this: if the surprise test were scheduled for Friday, by the end of school hours on Thursday we'd know the test must take place the next day, so it would not be a surprise. Therefore, we can rule out Friday as the day of the surprise test. Now we're down to the same problem with a four-day week (Monday through Thursday). If the surprise test doesn't take place by the end of Wednesday, we'd know it must be scheduled for Thursday, so it would not be a surprise. So we can rule out Thursday as well. And using the same argument, we can rule out Wednesday, Tuesday and Monday. We conclude that no surprise test is possible.

On the other hand, if the teacher sets the test on Wednesday, there seems to be no way the students could actually know this ahead of time. So something is screwy about the logic. Is this a case of Paradox Lost or Paradox Regained?

I think it's an example of something that looks like a paradox but isn't. Let's consider a restatement of the problem that is logically equivalent. Suppose that each morning the students announce confidently, "The test will be today." Eventually they will do so on the day of the test, at which point they will be able to claim that the test was not a surprise. This statement is a cheat—it's true but trivial. If every day you expect the surprise to happen, then naturally you won't be surprised. My view—and I've argued with many mathematicians on this subject—is that the Surprise Test paradox involves the same cheat, but it's dressed up to look mysterious. The cheat is simply less obvious because everything is intuited instead of acted on.

I'm suggesting two things here. The less interesting one is that this paradox hinges on what we mean by "surprise." The more interesting claim is that whatever reasonable thing we mean by "surprise," there are two logically equivalent ways to state the students' prediction strategy. One is the usual way to present the puzzle, which seems to indicate a genuine paradox. The other, which presents the problem in terms of real actions instead of hypothetical ones, turns it into something correct but unremarkable, destroying the element of paradox.

To illustrate my point, I'll add another condition to the Surprise Test paradox. Suppose that the students have poor memories, so that any work they do on a given evening to prepare for the test is forgotten by the next evening. If, as the students claim, the test is not going to be a surprise, they should wait until the evening before the test to do their studying. But if they don't study on Sunday evening and the test is on Monday, they'll fail. The same is true for Monday through Thursday evenings. So despite never being surprised by the test, the students have to study five evenings in a row.

Paradox Lost, I'd say. SA

READER_FEEDBACK

Many readers were baffled by my statement in "Most-Perfect Magic Squares" [November 1999] that a magic square cannot be pandiagonal unless its order is doubly even. As Colin R. J. Singleton of Sheffield, England, points out, classic texts such as W. W. Rouse Ball's *Mathematical Recreations and Essays* include constructions for odd-order pandiagonal magic squares. (An example of an order-5 pandiagonal square is shown at the right.) Sorry. What I meant to say was that *even-order* magic squares cannot be pandiagonal unless their order is doubly even. —*I.S.*

6	19	2	10	23
12	20	8	16	4
18	1	14	22	5
24	7	15	3	11
0	13	21	9	17

Books

REVIEWER_LEIGH VAN VALEN

How the Left Got Darwin Wrong

Philosopher **Peter Singer** argues that the Left must radically revise its outdated view of human nature

Any intrusion of ideology into science is an invitation to wishful thinking. In his powerfully argued *A Darwinian Left,* Peter Singer takes the opposite tack: How can science make ideology realistic rather than a pipe dream? Ideologies claim to be realistic, and by selectively picking what fits and ignoring whatever doesn't fit they commonly give themselves a veneer of intellectual respectability. Social Darwinism (always a misnomer) used to provide such a veneer for the socioeconomic Right, which has more recently adopted competitive efficiency for maximal growth in our too too finite world. In either case, might makes Right.

To Singer, and to me, the core of the Left is a set of values, most notably that worth is intrinsic and doesn't depend on success or power. Traditionally, various factual beliefs have been accreted to these values, such as the homogeneity of human nature and its perfectibility by social change. Because they are matters of fact, they can be empirically investigated. Indeed, on strong current evidence both these beliefs appear to be false. Singer devotes a substantial part of his 70-page book to setting the background for such revisions.

The gist of his subsequent argument goes something like this: It is quixotic to try to eliminate features that are pretty much universal among cultures, such as self-interest, a system of social rank, or even sexual jealousy. Among such quasi-invariants, though, is a readiness to form cooperative relationships and to recognize reciprocal obligations. Although the relative importance of cooperation and competition varies appreciably among cultures, it is by using cooperation as a focus that we may have our best chance for a real foundation for social change.

BETH PHILLIPS

A Darwinian Left: Politics, Evolution and Cooperation
by Peter Singer
***Darwinism Today* series**
Yale University Press, New Haven, Conn., 2000 ($9.95)

With cooperation, Singer argues, always comes the problem of cheaters, who take but don't give. Less inequality can probably reduce their number but not remove the problem: self-interest is powerful. To harness self-interest so that it promotes cooperation, it is probably necessary to make cheating unprofitable. Thus, we have jails and other sanctions (although Singer fails to make these explicit) for when cheaters aren't personally accessible. For cooperation is valued by more than the Left.

So what does all this have to do with the processes of biological evolution? I confess to being somewhat mystified, apart from its help with the cleansing of factual beliefs. A sophisticated treatment of cooperation, and its problems, exists in sociology. That treatment is more readily adapted than what we see in evolution. In the natural world, cooperation can in fact come from diverse evolutionary processes.

A species of bacterium may produce a waste product that inhibits its expansion if not removed. A second bacterium uses this waste as its own food, thereby benefiting both. Or when times get tough, some amoebae gather together and produce a stalked fruiting body from which spores have a chance to reach some fresh amoeba-size pasture. Or an alga and a

EXCERPT_*A DARWINIAN LEFT*

"A Darwinian left would not:

- *Deny the existence of a human nature, nor insist that human nature is inherently good, nor that it is infinitely malleable;*
- *Expect to end all conflict and strife between human beings, whether by political revolution, social change, or better education;*
- *Assume that all inequalities are due to discrimination, prejudice, oppression or social conditioning. Some will be, but this cannot be assumed in every case;*

A Darwinian left would:

- *Accept that there is such a thing as human nature, and seek to find out more about it, so that policies can be grounded on the best available evidence of what human beings are like;*
- *Reject any inference from what is "natural" to what is "right";*
- *Expect that, under different social and economic systems, many people will act competitively in order to enhance their own status, gain a position of power, and/or advance their interests and those of their kin;*
- *Expect that, regardless of the social and economic system in which they live, most people will respond positively to genuine opportunities to enter into mutually beneficial forms of cooperation;*
- *Promote structures that foster cooperation rather than competition, and attempt to channel competition into socially desirable ends;*
- *Recognise that the way in which we exploit nonhuman animals is a legacy of a pre-Darwinian past that exaggerated the gulf between humans and other animals, and therefore work towards a higher moral status for nonhuman animals, and a less anthropocentric view of our dominance over nature;*
- *Stand by the traditional values of the left by being on the side of the weak, poor and oppressed, but think very carefully about what social and economic changes will really work to benefit them."*

fungus may form a lichen that can live where neither component can survive by itself. Or some fish are less likely to be found and eaten if they are in a school. Or a pack of wolves can overcome a caribou that would be dangerous to one alone. Or a beetle may eat pollen and transfer some to the next flower it visits. Or a subordinate female of a paper wasp that gets uppity and lays an egg of her own may have it eaten by the dominant female to enforce cooperation. Or a soil fungus that helps plants absorb nutrients and gains energy from them in return may transfer nutrients from a more successful plant to a weakling, thus imposing cooperation. Or a honeybee that stings usually then dies in the process, for the sake of its relatives. Various other causes of cooperation are found in nature, some less easy to visualize.

Some of these processes apply in human societies, too. Family members tend to cooperate with one another more than with nonrelatives, drafted soldiers form an army unit by coercion, and so on. Singer quite ignores this background diversity and reasonably so. It isn't what our societies are built from, mostly.

In the biological world, cooperation is almost always merely a mechanism of competition. The only class of exceptions I know is when cooperation permits use of resources that would otherwise go unused, as with a lichen on a bare rock. Every species and population expands until something stops it. If cooperation permits more expansion, then it is automatically selected for. Otherwise it isn't.

As Singer points out, Karl Marx and others have noted that Darwin's theory has important resemblances to English society of the time, with such phenomena as competition, division of labor, and expansion of successful novelties. The theory has been maligned because of this resemblance, yet it has been magnificently vindicated and survives unchanged in its basic form. So we can turn the critique on its head: rather than the resemblance impugning what we know of evolution, it was probably important in locating the initial discovery in England at that time. Alfred Russel Wallace, co-discoverer of the theory of evolution by natural selection, was English, too, and both he and Darwin had their basic insight when reading *On Population,* by Englishman Thomas Malthus.

Does the primacy of competition over cooperation in nature mean that the Right is right? Not at all. A study of evolution is useful in debunking factual beliefs of the Right as well as of the Left. In addition, we can exert our dominion over fish and fowl not literally but by transcending the automatic processes of the biological world. We don't need to use the natural world as a model for our actions, still less as a model for our values. We are superior only because of the brains that permit us to make general choices as well as specific ones. If we jointly prefer a cooperative approach to a competitive one, we have the ability to modify our society for the good of all. Thus, we can choose to transcend our heritage; *is* never justifies *ought.*

It is a truism that we don't own the earth but borrow it from our children, a truism that embodies the spirit of cooperation and resonates deeply with the Left.

LEIGH VAN VALEN is professor of ecology and evolution and of the conceptual foundations of science at the University of Chicago.

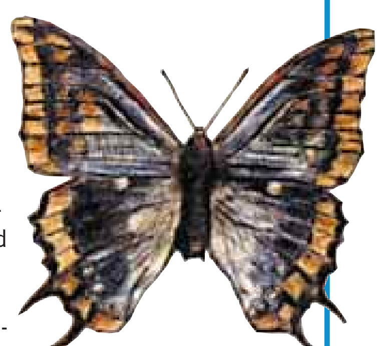
THE EDITORS_RECOMMEND

ABRAHAM PAIS'S *The Genius of Science: A Portrait Gallery.* Oxford University Press, New York, 2000 ($30).

Pais, himself an eminent physicist, writes about 16 of his contemporaries—some famous (Albert Einstein, Niels Bohr and John von Neumann among them) and some not widely known outside the scientific community. Because he knew each of the 16, he is able to provide personal touches that another biographer would miss. The first time he talked physics with Bohr, for example, he thought that Bohr had not been much interested. "At a later stage I would have known right away that his curiosity was aroused, as he had neither remarked that this was very interesting nor said that we agreed much more than I thought—his favorite ways of expressing that he did not believe what he was told." Von Neumann, Pais says, "introduced me to a favorite word game of his: find the *nebbish* value of a sentence." That Yiddish word means something like a compassionate "that's too bad," and the game is to find the ratio of the number of words in a phrase to the number of times one can insert "nebbish" in a way that enhances the meaning of a sentence. "His favorite example, a phrase with maximal ratio one: *cogito nebbish, ergo nebbish, sum nebbish.*" These touches make for more entertaining reading than one might expect from a recital of the achievements of 16 physicists. (Von Neumann is known chiefly as a mathematician, but in his early years his focus was on physics.) Pais is also good at describing those achievements in each case, and so the reader comes away both entertained and instructed.

Nabokov's Butterflies: Unpublished and Uncollected Writings. Vladimir Nabokov (edited and annotated by Brian Boyd and Robert Michael Pyle). Beacon Press, Boston, Mass., 1999 ($45).

Most readers of Nabokov (the Russian-American author of *Lolita* and other highly regarded works of fiction) know that he was interested in butterflies, but it is doubtful that many of them are aware that the level of his knowledge and his contributions to the field won the respect of professional lepidopterists. Nabokov himself showed the depth of his work in a letter of 1943 to literary critic Edmund Wilson. "A summary of part of my scientific work on the Blues (the *Lycaeides* genus—"Silver Studded Blues" in English) ... is due to appear in a week or two. The labour involved has been immense; the number of my index cards exceeds a thousand references—for half a dozen (very polytypic) species; I have dissected and drawn the genitalia of 360 specimens and unraveled taxonomic adventures that read like a novel."



FROM NABOKOV'S BUTTERFLIES

The book that Boyd and Pyle have put together gives a good picture of Nabokov's lepidoptery and reproduces many of his drawings. It also offers much else in letters from and to him about a variety of topics, in excerpts from interviews he gave, and in his poems and prose on subjects other than butterflies. An excellent companion to this compilation is *Nabokov's Blues: The Scientific Odyssey of a Literary Genius,* by Kurt Johnson, a lepidopterist who occupied Nabokov's former office at the American Museum of Natural History, and writer Steven Coates (published in 1999 by Zoland Books in Cambridge, Mass.).

DAVID E. H. JONES'S *The Further Inventions of Daedalus: A Compendium of Plausible Schemes.* Oxford University Press, New York, 1999 ($15.95).

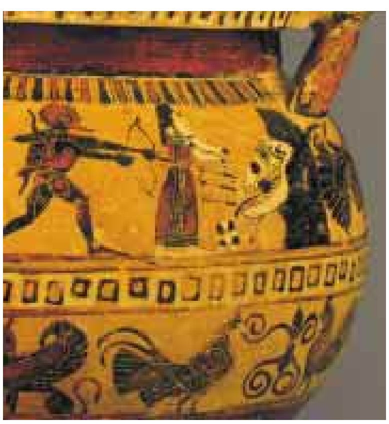
Jones, who has turned out the weekly "Daedalus" column in British publications since 1964, sees himself as "the court jester in the Palace of Science." Each of his columns proposes some scientific scheme designed to confront accepted notions of technical feasibility. Appearing in *New Scientist* from 1964 to 1988, in *Nature* and the *Guardian* until 1996, and in *Nature* alone since then, the columns now number more than 1,700. From them, Jones has chosen 101, revised them, added comments, and drawn pictures or diagrams to accompany most of them. He says the columns aim at "a region of scientific humour whose appeal lay in its closeness to reality." And so he goes on about such topics as the solid-liquid diet, a dance to the music of space-time, and herbal petrol. The columns will evoke plenty of chuckles from the reader while dispensing plenty of sound scientific information.

KARL LUNT'S *Build Your Own Robot!* A. K. Peters, Natick, Mass., 2000 ($34).

Personal robots are about as advanced today as personal computers were on the eve of the first IBM PC in the early 1980s. They are still the domain of hobbyists who cobble them together from scratch or from kits (available through such vendors as robotstore.com), who join local clubs to swap code and stage contests, and whose labor of love is setting the stage for a technological revolution. There is even an analogy to the Apple II, a ready-made, almost mass-market product: the Cye robot. And two companies, Dyson and Eureka, are beta-testing the first potential killer app: automated vacuum cleaning. Lunt's former column from *Nuts & Volts* magazine—all five years of the column are reprinted in this volume—has been to robot hobbyists what *Byte* and *Popular Electronics* were to computer hobbyists. Along with Joseph Jones and Anita Flynn's *Mobile Robots,* his book serves as an essential guide for those who want to build their own blinking, buzzing, bumbling artificial pets.

ADRIENNE MAYOR'S *The First Fossil Hunters: Paleontology in Greek and Roman Times.* Princeton University Press, Princeton, N.J., 2000 ($35).

The history of paleontology, as it is usually seen, starts with the work of French naturalist Georges Cuvier some 200 years ago. Mayor, a classical folklorist, moves the date back to the time of the ancient Greeks and Romans. "The ancients collected, measured, displayed, and pondered the bones of extinct beasts," she writes, "and they recorded their discoveries and imaginative interpretations of the fossil remains in numerous writings that survive today." Among the beasts whose bones they pondered were giant giraffes, mammoths and mastodons.

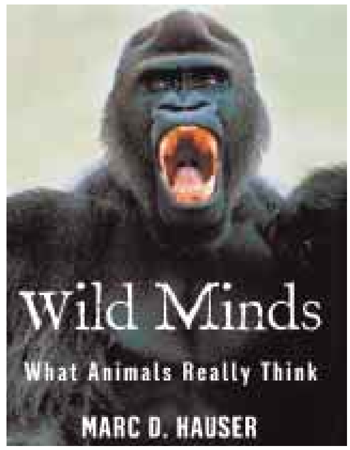


FROM *THE FIRST FOSSIL HUNTERS*

Mayor also proposes that the griffin of classical folklore, described in the legends as having the body of a lion and the beak of an eagle, "was based on illiterate nomads' observations of dinosaur skeletons in the deserts of Central Asia." And she tells of purely imaginary creatures of the classical period, such as the triton and the centaur. But her focus is on what the ancients made of the bones of real animals. Advances in classical studies and paleontology, she says, "now make it possible to restore the ancient fossil investigations to their rightful place in the history of science."

MARC D. HAUSER'S *Wild Minds: What Animals Really Think.* Henry Holt and Company, New York, 2000 ($25).

One can find people, usually not scientists, who tell of psychic dogs and cats, weeping elephants, mischievous monkeys, altruistic dolphins and moralistic apes. And one can find people, usually scientists, who hold that animals are mindless and irrational, driven by instinct and overwhelmed by their passions. Hauser, who is a professor of psychology at Harvard University and a close observer of a variety of animals in action, takes a middle ground. "All animals are equipped with a set of mental tools for solving ecological and social problems," he writes. "Some of the tools for thinking are universal, shared by insects, fish, reptiles, birds, and mammals, including humans. The universal toolkit provides animals with a basic capacity to recognize objects, count, and navigate." He depicts the use of the toolkit with fascinating descriptions of the activities of chimpanzees and other primates, lions, bats, birds, bees and various other creatures as they go about their business.



ROBERT WRIGHT'S *Nonzero: The Logic of Human Destiny.* Pantheon Books, New York, 2000 ($27.50).

Many people, particularly scientists, share physicist Steven Weinberg's view that "the more the universe seems comprehensible, the more it also seems pointless." Wright, a writer whose best-known book is *The Moral Animal,* is not one of them. "The more closely we examine the drift of biological evolution, and, especially, the drift of human history," he writes, "the more there seems to be a point to it all." Evolution, he says, has a tendency to create forms of life that feature greater and greater complexity, culminating (at least so far) in life-forms that think and write about such things. He finds the driving force for all this in game theory. "In non-zero-sum games, one player's gain needn't be bad news for the other(s)." And that is the root of the cooperation that has led to the present state of cultural evolution.

This line of thinking leads Wright inexorably to ask if there is "a directionality suggestive of purpose" in the universe. His answer: "A strictly empirical analysis of both organic and cultural evolution ... reveals a world with direction—a direction suggestive of purpose, even (faintly) suggestive of benign purpose."

The Internet as Hardware

Philip & Phylis Morrison take a cyber-pinging journey among Web sites near and far

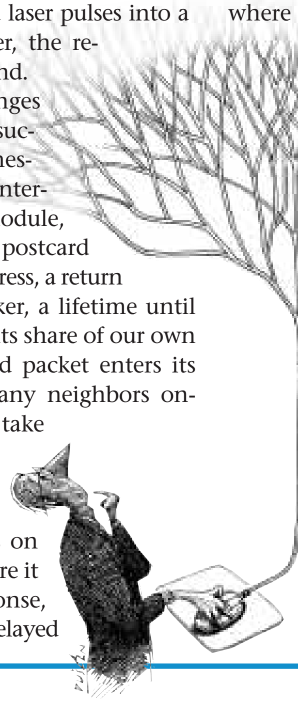
We share a long, flat townhouse roof and a single facade with eight neighbors. Power, telephone and cable TV lines tie all the households to streetside poles. Two homes have cable modems; a coaxial cable runs out to a windowless room in an apartment house up the street, where we go on-line 24/7, without dial-up, along with many another well-wired resident of the surrounding city blocks. From that room a major Internet service provider, MediaOne, places us on optical fiber. Our pulses fly out at rates several times what a telephone modem carries; we download at a faster rate still, more than 50 book pages or a couple of acceptable images in one second. Usually, with no noticeable delay, a few dozen keystrokes will get us where we wish to go and back again.

In this column, we lift the software curtain for a glimpse at its physical essentials, intricate intercontinental structures that realize what we so artlessly begin. When Web browser–engaged, our desktop computer sends coded pulses out with little coaxing. Unattended boxes nearby process our electrical signals and reenter them as equivalent infrared laser pulses into a thin, transparent fiber, the reverse occurring inbound.

The browser arranges our keystrokes into a succession of modular messages conforming to Internet Protocol. Each module, called a packet, is of postcard length; it bears an address, a return address, a place marker, a lifetime until erasure en route and its share of our own message. The infrared packet enters its queue—recall our many neighbors online, whose packets take their turn among ours as they appear—to mingle with the photon stream that goes on to the next node. There it might elicit a response, more often than not relayed toward its final address, or die in a failed attempt. Each packet flies by in one or two milliseconds into our neighborhood optical fiber, to reappear sorted into correct order at its destination.

It is the inordinate speed of electronics that supports our illusion of simple, swift action at a distance. But in truth, an unceasing sorting and shuffling of myriads of structured packets is at work between your computer and some distant PC-like box, the server. That box serves you from its store of a whole bookcase of ready pages. A server and its transient client become briefly two terminals of an Internet connection, one at your fingertips, the other as requested, though not always from the physical location you expected. The elaborate path of storing and forwarding depends on a changing physical fabric. The packets are sent on to nodes where specialized machines, called routers, select the path segments ahead from long internal directories, while they store for relay the streams of petitioning packets, prioritizing them as best they can to speed the traffic of the moment along each route.

> ***It is the inordinate speed of electronics that supports our illusion of simple, swift action at a distance.***



We have experimented with a Web shareware program, NeoTrace, which sends to any URL a message that "pings"—elicits a roll-call response—at each node in turn. The screen reports the nodes and the round-trip time to each, including all delays, and looks up their approximate location and manager, when known, to offer a casual snapshot of one real thread of Web tapestry. Like some royal father in a fairy tale, we sent pings on journeys to World Wide Web sites near and far. We often start on MediaOne fiber to reach our busy old home network, mit.edu. Our packets come into one humming, windowless room at the edge of campus, filled—but not yet crowded—with rows of relay racks claimed by servers and routers, glowing diodes in plenty, and cables diving under the floor.

Our most daring test trace crossed both the Atlantic and the Equator over 25 nodes to a major South African newspaper. The first four nodes were shared by all our journeys, fast initial optical-cable steps, some 10 to 20 milliseconds of relaying and waiting. With node 6, we entered a new net, registered to AT&T, and for a few steps moved amid midcontinental traffic, until near Dallas we were passed on to Teleglobe Canada, a Montreal-based Net service provider, for half a dozen steps eastward. Africa appeared within the next three steps—here we noted the largest delays, up to 600 milliseconds, most likely a satellite segment—until we reached the servers that hold the Web site of the *Mail and Guardian* in Cape Town.

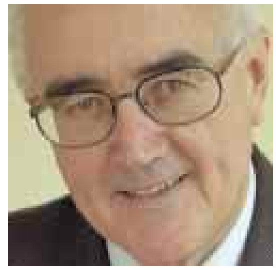
Often we found unexpected jogs. We have pinged to Virginia and back to reach Harvard, just a mile away. When once we sought a celebrated Seattle destination, we were served from somewhere near Montreal. (We surmise the material we sought had been stored remotely for good reason.) Internet cartography is patently difficult. The best map we found (www.cs.bell-labs.com/who/ches/map), compiled by heroic pinging, impresses the eye as a grand collection of local complexes wherein many tendrils join. Across that wide graphic, dozens of longer paths dodge their angular ways, identified as principal Internet service providers.

Continued on page 115

DUSAN PETRICIC

All at Sea

Yo-ho-ho and a bottle of rum—buried treasure and pirates, novelists and politics—**James Burke** tours life on the high seas



DAVE PAGE

Not long ago I was crossing the Atlantic the comfortable way, on board the liner *Queen Elizabeth II* (filming, not cruising, as it happens), and at one point in one of the ship's many comfortable bars I thought I'd go a bit nautical and have a glass of rum.

Which brought to mind the fact that one of the first people to import rum and molasses to Philadelphia in the early 18th century was a Prussian immigrant named Thones Kunders, who it is said got a taste for his business (and more) after overhearing a couple of villainous-looking pirate types discussing peg legs, keel hauling, buried treasure, etc. But not just any old buried treasure. The fabled (and at the time unrecovered) ill-gottens of one Edward Teach, a.k.a. Blackbeard. So Kunders (the story goes) went and dug it up, and quicker than yo-ho-ho he was in the import-export business, with a small merchant fleet, and doing nicely, thank you. More than can be said for Blackbeard himself, who started as one of the first Spanish Main pirates (raiding, pillaging, torturing anything and anybody in the Caribbean, Virginia and the Carolinas). And who finished not much later (captured and decapitated).

This was after he'd foolishly turned down an amnesty offer from Woodes Rogers, governor of the Bahamas, which (get this!) Rogers had *rented* from the islands' owners, having made a ton of money on semi-pirate contract to some English merchants to sail the Pacific and knock off any Spanish ship he came across that was carrying anything worth knocking off. (As it happens, one of Rogers's not so *semi*-pirate crew was buccaneer William Dampier, whom I've mentioned before in connection with the College of William and Mary. Which connection, to save the college blushes, I won't mention again.) In January 1709, during his Pacific jaunt, Rogers hove to by San Fernandez, a desert island off the Chilean coast. The boat he sent ashore came back with a half-crazy guy in goatskins who could hardly speak English anymore and who had been marooned there four years earlier by (amazing coincidence I doubt) a ship carrying William Dampier, who now recommended he be made ship's mate.

The following year they were back in London, and the new mate, Alexander Selkirk, went ashore with enough booty to disappear into a nondescript rest-of-life. Except for a mention of him in Rogers's widely read journal, which is why you know Selkirk by another name: Robinson Crusoe. The hero of what is arguably the first English novel, by an author who had read Rogers's piece: Daniel Defoe. Who was so many things it's hard to say what not: bankrupt, satirist, magazine editor, pamphleteer, political columnist who made enemies on both sides of the fence he sat on, stocking salesman, deflater of the puffed-up, and all-around good egg. At one point he was hired by Robert Harley (running England at the time) as an intelligence agent, to report on any political skulduggery by Scots at the time of their 1707 union with England. He spied so well that Harley used Defoe's weekly political mag, *The Review*, to spin-doctor the government's public relations.

Harley also thought up another crafty scam. He raised a massive loan from the Stock Exchange to cover much of the National Debt (humongous and getting more so thanks to war with the French). This smoke-and-mirrors financial arrangement became the subject of more serious study later in the 18th century, when the new actuaries got their math off the ground and a Welshman named Richard Price turned out a weighty tome, one bit of which described what it would take to establish a sinking fund to service the Debt. I don't understand his stuff, so that's all I can say. More generally, however, Price's book made life easier for widows by putting the life insurance business on a more-than-guesswork footing (with a massive study of some well-kept parish registers of births and deaths), when Price included what insurers needed to stay solvent: life tables that would help them to work out premiums that bore some realistic relation to life expectancy. If they're going to live long, drop your price, Price said. Charges dropped, income rose. This made Price very popular in financial circles. His other work (a spirited defense of the American rebels) got him an invitation to act as financial consultant to the U.S. Congress (he refused) and to accept a doctorate from Yale, together with George Washington (he accepted).

She taught poor children to read but not to write. You get the point.

At one point Price got taken under the wing of a formidable lady, Mrs. Elizabeth Montagu, the hostess with the mostest in London at the time. Her "conversation parties" were the rage of the chattering classes and attended by anybody who was anybody. Even women were allowed to say their piece, and those who did, often and at length, formed a kind of

PATRICIA J. WYNNE

club-within-a-club, and all wore blue stockings. Hence the term. One of these ladies was Hannah More, well known for her radical tracts and less well known for having started Sunday schools. At which she taught poor children to read but not to write. You get the point. Hannah tackled issues from piety to women's education to general self-improvement to slavery (she was against it). One of her heroes was Granville Sharp, who spent most of his life and money on "liberal" issues such as American independence (pro), press-gangs (con), conversion of Jews (pro), something arcane involving Greek grammar and the Bible and, above all, the abolition of slavery.

Earlier, in 1772, he had fought the case of James Somersett, a runaway slave, and got the famous ruling: "As soon as any slave sets foot upon English territory, he becomes free." As a result of which, by 1787 the number of freed slaves in England was embarrassing. So Sharp thought up the Sierra Leone Company. And that year the first cargo of 400 freed slaves shipped out for the return journey to Africa, settling in what would become Freetown.

The word got around, and five years later Freetown welcomed more black runaways. This time from Halifax, Nova Scotia, to which they had earlier run away at the end of the War of Independence, chased out by disgruntled American Revolutionaries who were unimpressed by the black Loyalist support for the English during that war. Other pro-English types were also "invited to leave" the new United States. Including a guy who had his family's merchant fleet impounded and went north to Halifax to start over.

He did very well, aided by the growth of shipping across the Atlantic (including that to Sierra Leone). And once lasting peace had been made between England and America and regular mail runs were required, he was in like Flynn. By the mid-19th century the company he had founded was the biggest on the route and just went on growing till it was launching the largest liners afloat. One of which, one day, turned out to be the *Queen Elizabeth II,* pride of the family line.

And by one of those ironies that makes history such a gas, the name of this shipping conglomerate wasn't the one it had started with. As so often happened with immigrants to America, the original family name was misspelled by some official. Who changed it to Cunard, from the Prussian: Kunders. SA

Wonders, *continued from page 113*

Once, when the Internet was simpler, it might have appeared as the nervous system of a vertebrate, with links branching from a single spine. But now it has too many backbones for that comparison to hold. Rather the resemblance is to some species' scattered burrows, linked through shifting, indirect routes, which here evade obstacles and there seek opportunities. Maybe this is no metaphor at all but an apt account of the Internet in space and time? Think crudely of a buried set of 100 or so long-range global networks that diversely link and transfer messages to and from more than a 10th of a million local networks, both in mutual interest and in sharp proprietary rivalry. In the end, the Internet joins tens of millions of users, quite a few of those "users" merely smart instruments making on-line reports.

The telephone common carriers, themselves digital at depth, are managers, landlords or partners to most big Internet providers. One multiplex optical cable is currently being tenderly buried along the Massachusetts Turnpike and the New York Thruway, just one new partnership building one new network. The trenching reminds passersby daily that the Internet on land is physically subterranean, hungry for rights of way where its glass and copper can be buried safely in conduit. True, there are also local wireless and orbiting satellite links, microwave tower relays, and millions of submarine miles of optical fibers that crisscross the undivided ocean floors. All these constitute the aggregate Internet.

That same infrastructure, its varied routes often cheek by jowl, also handles credit cards, market transactions, news, weather and space data, e-mail and more, more, more—mostly over distinct, dedicated "leased channels." A special subset of the entire Internet, defined by its remarkably flexible software, is the World Wide Web, in whose service so many packets diffuse at large throughout the physical Internet among some 10 million Web sites. Our sketchy account of this vast symbiosis is a traveler's honest report, and not much more.

We are grateful to the information professionals who have explained these matters to us: our neighbors Bob and Jane Morse, Professor Alva Couch of Tufts University, and the managers who support our old site, Jeff Schiller of M.I.T. and John Hawkinson of GTE. SA

JEFF JOHNSON (*illustrations*); NASA (*photograph*)

DAN WAGNER

Great Feets

Walking on water, **Steve Mirsky** finds, takes a man with mighty big shoes to fill

Fish gotta swim. Birds gotta fly. What doesn't gotta happen is what an Alsatian man named Rémy Bricka likes to do—walk on water. In March, Bricka began what he hoped would be a walk, on buoyant ski-length footgear, across the Pacific Ocean. Because it is there, presumably.

Bricka already holds a place in the *Guinness Book of Records* by virtue of a previous tromp across the Atlantic in 1988. Normal journalistic practice would include an attempt to reach Bricka for a first-person account. That idea ground to a halt upon contemplation of the words of linguistic philosopher Ludwig Wittgenstein: "If a lion could talk, we would not understand it." Just as the uniquely leonine experience imposes a worldview that would make meaningful communication impossible, the Bricka experience probably placed him beyond my comprehension. My father really is a carpenter who really is named Joseph, but any messiah complex I may have is too puny to help me figure out why somebody wants to walk on water. And I haven't even mentioned that Bricka takes leave from his job as a one-man band to take his walks.

Actually, lots of guys walk on water all the time. They are called hockey players. But restricting the discussion to water in the liquid phase, your average human makes a poor pond pedestrian. Bricka's passion, however, made me wonder about the creatures—none great, all small—that truly can keep their feet above water.

Such animals exploit various physical principles to stay afloat. Robert B. Suter, a biologist at Vassar College, studies one such critter, the aptly named fishing spider. He explains that its legs produce tiny dimples on the water thanks to surface tension, the slight attraction of water molecules to one another that becomes a Brobdingnagian factor at Lilliputian scales. "What makes the dimple stay intact is surface tension, and a lot of the force that holds the spider up is surface tension," Suter says. Add the water's drag, and when the spider drives a leg against its dimple, voilà, it's walking.

Although there are characteristics of rowing involved here, and despite the fact that the dimples also act as hulls and impart an additional slight buoyancy, this process seems much like the kind of walking with which we humans are familiar. A leg pushes against a surface that pushes back. So while I hate to burst his bubble, Bricka's walks seem misclassified. He is actually a conventional sailor sailing unconventional vessels: two boats that happen to fit on his feet.

Your average human makes a poor pond pedestrian.

On the other hand, Bricka could become a genuine water walker through modified gear that would allow surface tension to work its magic. He needs to get edgier, the edge in question being where water, air and foot meet and where surface tension does its stuff. Calculations, for freshwater, by Mark W. Denny of Stanford University show that a 110-pound person could walk on water using footwear with a total perimeter of about 6.7 kilometers. Laces surely sold separately. A bigger challenge than walking the Pacific would then be wearing both shoes at the same time.

An alternative noted by Steven Vogel of Duke University is severe weight reduction. Assuming Bricka wears about a size 9, his feet alone would support him on the water if he managed to slim down to about five grams, an accomplishment that would render the ensuing Pacific walk a mere footnote.

All this advice comes too late. Bricka's march on the sea, which he had estimated would take six months, was over almost before he could wave good-bye. On day one, a storm wrecked the catamaran he towed behind him, costing him food, supplies and bed. And so his *mare* trek came to an end. Fortunately, he escaped unscathed and continues to walk among us. Because he didn't sink. Like a bricka. SA

THE SECOND HALF OF ALFRED NOBEL'S WILL IS DISCOVERED

SIDNEY HARRIS

End Point