NUCLEAR ENERGY'S NEXT GENERATION • THE ECONOMICS OF FAIR PLAY

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EXCLUSIVE REPORT

THE FIRST Human Clone

The Clone Makers Tell Their Story

PLUS:

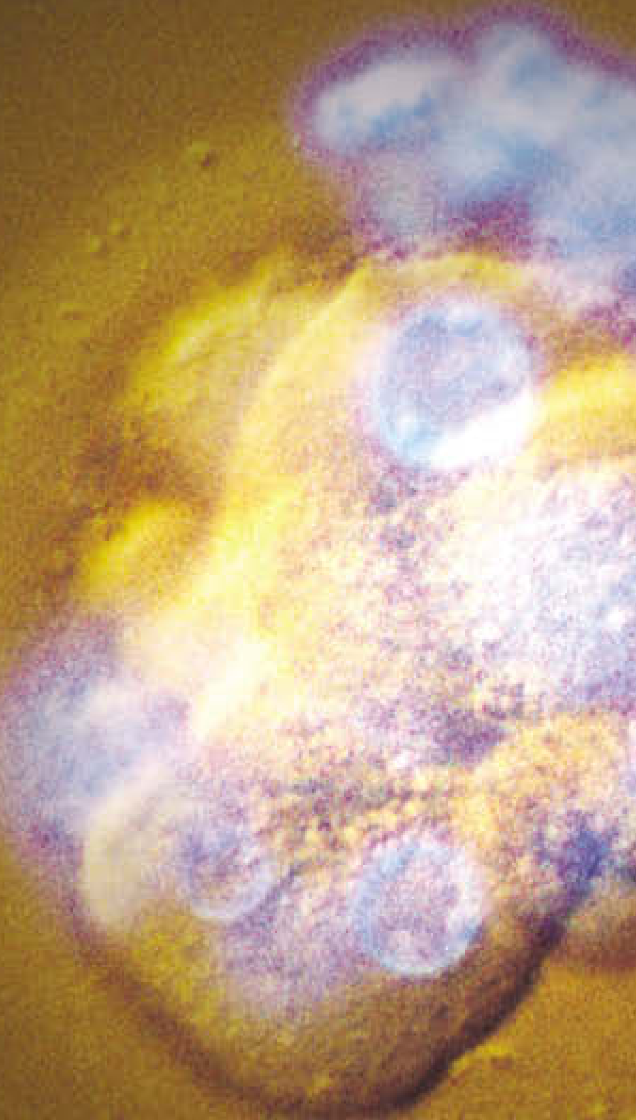
Between the Stars

Answering the Skeptical Environmentalist january 2002

contents

features

SCIENTIFIC AMERICAN Volume 286 Number 1



44 Cloned six-cell human embryo

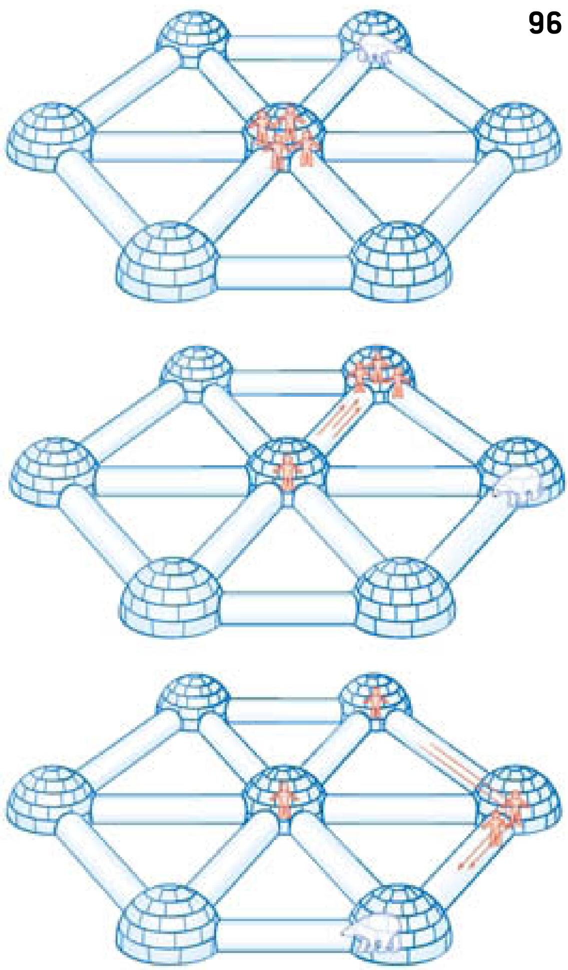
SCIENTIFIC AMERICAN Volume 286 Number 1

departments

DNA sequencer

Doug Lenat

96



columns

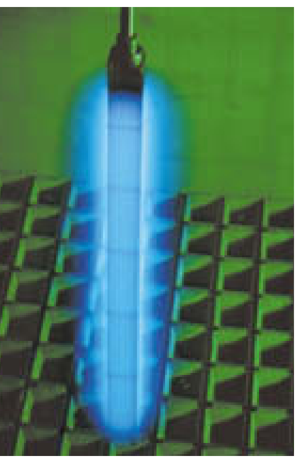
Cover photograph and preceding page by Jose B. Cibelli; this page, clockwise from top left: Kay Chernush; Dan Cohen; Sara Chen

SA Perspectives

Is Nuclear Power Ready?

Nuclear power doesn't usually conjure up the most positive images, so its recent rehabilitation has been all the more notable. The Bush administration has called for a greater reliance on nuclear power, which today generates one fifth of U.S. electricity supplies. Not only could splitting the atom satisfy our burgeoning energy needs, advocates say, it could also reduce the risk of global warming from fossil-fuel burning.

Maybe. Certainly new, safer and potentially more economical reactor designs such as those discussed in this issue [*see page 70*] could help ease the public's apprehension. But planners must resolve some critical concerns before we can say whether nuclear energy is up to the task.



WANTED: 10,000-year home for spent nuclear fuel rods.

Where can we put all that nuclear waste? This has always been the industry's hot potato—perhaps too literally for comfort. The nation's 103 nuclear power plants each generate an average of around 20 tons of radioactive spent fuel a year. Spent fuel now sits in cooling pools and temporary storage areas waiting for somebody to figure out what to do with it. By the end of 2001 the U.S. Department of Energy was to have ruled on the suitability of the only site being considered for a national repository: Yucca Mountain, a desert ridge of volcanic rock located 90 miles northwest of Las Vegas. In the latest plan, 70,000 metric tons of nuclear waste would be stashed in tunnels drilled 300 meters below the mountain's crest and 300 meters above the water table.

Two decades and $7 billion after site studies began, researchers are still not sure that the Yucca complex and its special storage vessels will contain the radiation and possible seepage of contaminated water for the 10,000 years required for the danger to start to subside. Further, vociferous objections of Nevadans emphasizing the potential threat of terrorists to cross-country shipments of radioactive materials now sound all too plausible. As it stands, Yucca could not start accepting used fuel until 2010.

A partial solution—though an expensive one—might be to reprocess the spent fuel for reuse. Britain, France and Japan have followed this route, but the U.S. has long resisted it because the operation produces plutonium, which terrorists and their state sponsors could divert to build bombs. New recycling techniques and breeder-reactor designs may, however, create fuels that would be useless in weapons.

Can nuclear power ever be cost-competitive? Far from providing energy that's "too cheap to meter," nuclear plants have been the most costly power option. The nuclear industry estimates that new plants must be built for less than $1,000 per kilowatt of electrical output to be economically practical. Some existing plants cost three times that amount. Future facilities will require not only more efficient reactors but also lower-cost construction.

Who will run tomorrow's nuclear plants? A 1997 DOE study found just 570 students majoring in nuclear engineering, down two thirds from five years earlier, though that trend may be flattening out. Teaching reactors at universities around the country have been shut down. Even if more nuclear plants are not built, someone is going to have to run the existing ones until they are taken out of service.

It is clear that any prospective nuclear renaissance will require some critical thinking to overcome the roadblocks. Naysayers must confront the all-too-real possibility of reduced energy supplies—and the accompanying decline in living standards—should these efforts fail.

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TIM WRIGHT *Corbis*

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Letters

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"THE INSISTENCE by Gary Stix in 'Little Big Science' that we discard 'the fluff about nanorobots' before ushering in a new industrial revolution misses the point," writes John Granacki of Ashland, Ore. "The fluffy nanorobots *are* the revolution, without which we are merely refining the microrevolution, already four decades in progress. Such visionary rhetoric may adversely affect funding, but the flaw must be recognized as being not in the science itself but rather in the funding process—the more progressive a concept, the greater the resistance from the status quo."

Additional discussions of matters nano may be found among the September 2001 letters below.

SELF-ASSEMBLY A RED HERRING?

One of the more questionable nanotechnologies involves the notion of self-assembling machinery ["Machine-Phase Nanotechnology," by K. Eric Drexler]. It would be more effective at this early stage to focus on creating a specialized set of highly efficient single-purpose tools. The industrial revolution provides a good parallel: the past century demonstrated the incredible efficiency of assembly lines, yet we don't ask factories to produce more factories; on the contrary, we simply add more assembly lines and stock them with single-purpose tools that are nothing more than mechanical idiots savants.

Of course, we have ample evidence that biological systems can be self-assembling, but even these systems are far too complex for us to easily replicate them at the microscale.

GEOFF HART
Pointe Claire, Quebec, Canada

UP WITH NANO

Several statements in "Nanobot Construction Crews," by Steven Ashley, and "Little Big Science," by Gary Stix, indicate a serious misunderstanding of Zyvex, its approach and its objectives. Zyvex is taking a systems approach to molecular nanotechnology. It has substantial research and development efforts in (1) manipulation and characterization of nanomaterials and nanostructures, (2) positionally controlled chemical reactions for the assembly of precise nanostructures and (3) MEMS and NEMS, to develop tools to handle molecular-scale subcomponents.

We think that practical application of molecular systems requires a viable interface to the "real world," which will require assembly capabilities from the millimeter to the nanometer scale.

JIM VON EHR
President and CEO, Zyvex Corporation
Richardson, Tex.

Richard E. Smalley ["Of Chemistry, Love and Nanobots"] writes that "self-replicating, mechanical nanobots are simply not possible in our world." But Smalley himself, like the rest of us, is composed largely of the self-replicating, mechanical nanobots that implement carbon-based life as we know it. If such nanobots were truly impossible, then there would be nobody here to deny their possibility.

LEE SPECTOR
School of Cognitive Science
Hampshire College

BITTER MEDICINE FOR NANOTECH BELIEVERS

Visionaries come in two flavors: down-to-earth and far-out. Richard Feynman, in his caveat-crammed lecture, belonged firmly in the first category. Drexler is a shameful example of the second. Biology does not show us that "molecular machine systems and their products can be made cheaply and in vast quantities." The R&D alone took hundreds of millions of years, uncountable mutations and massive extinctions. Nanotechnology presupposes design; biological processes derive from evolution.

Also, the problem of energy deserves more attention than a dismissive "these are reasonable questions" or cheap speculations on exotic alternatives. And as to "vital societal questions," a reality check is required here: no social rule applies before the fact or can be based on fiction. That way lies tyranny. Let people create nanomachines first, as described, if and when they can, and humanity will adapt. No need for self-appointed prophets and legislators.

FLAVIO ZANCHI
Retford, England

LA CREME DE L'OREO

"Little Big Science," by Gary Stix, mentions the "cream filling in an Oreo." I believe, though, that the proper spelling is "creme," as I'm sure there is a regulation requiring foods with the former spelling to have a certain percentage of milk product, and I'm equally sure that cows come nowhere within a 50-mile radius of the Oreo-making process. Indeed, I suspect that Oreo "creme" may itself constitute a form of matter apart from the others known to science, and guided by its own physical laws.

PETER B. KAUFMAN
Brooklyn, N.Y.

UNTRACEABLE ACCOUNTABILITY

Wendy M. Grossman ["Surveillance by Design," News Scan] floats the old canard that traceable cash is a bad thing. It would be interesting to research the extent to which the nontraceability of money throughout the ages has facilitated crime and corruption. Note, for instance, the case of Al Capone, who could be brought to book only when the tax authorities demanded traceability of his assets. Whatever views one may have on drugs themselves, the huge effort made by American and other governments to try to prevent laundering of drug money indicates the extent to which the establishment feels threatened by truly liquid cash when faced with it as a reality.

PETER R. ROWLAND
London

MOSQUITOES AND HIV

A number of readers responded to my answer to the question "If a used needle can transmit HIV, why can't a mosquito?" [Endpoints] by asking whether HIV can survive in a drop of blood on a mosquito's mouth the way it can inside a used needle or syringe. The amount of blood left on a mosquito's mouth is quite small; accordingly, the potential virus load is small. In addition, HIV is inactivated by drying—thus, mechanical transmission would have to take place very rapidly from human to mosquito and back to human. Fortunately, epidemiological experience over the past 20 years has confirmed that HIV is not transmitted by mosquitoes. Other viruses, such as dengue and West Nile, can replicate in insects and do pose a threat of transmission via this route. For these viruses, the mosquito serves as a replicating vector, not a mechanical vector.

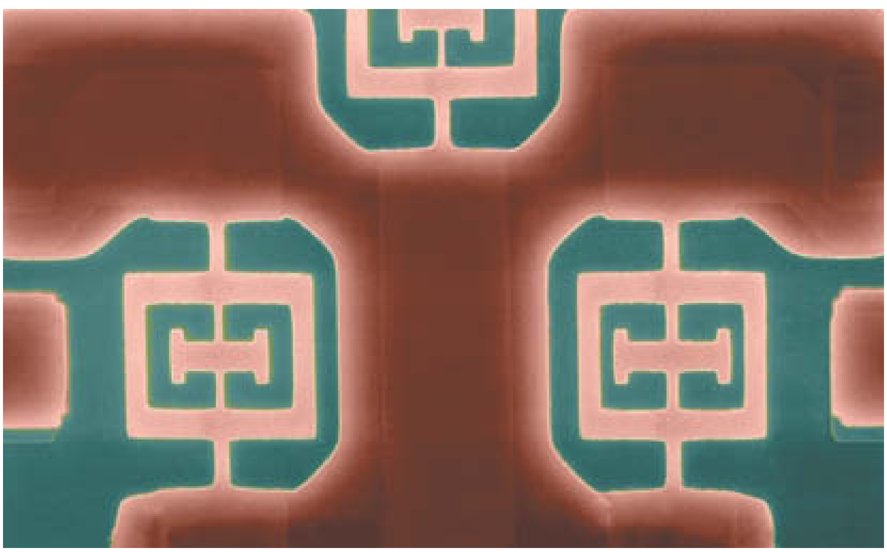
LAURENCE CORASH
Chief Medical Officer, Cerus Corporation
Concord, Calif.

SAFE FOOD, COURTESY OF HACCP

As a health department sanitarian who has done restaurant inspections and kept track of foodborne-illness surveillance data for 22 years, I can say with some assurance that Winkler G. Weinberg's suggestion that education about known control methods might make *E. coli* "just go away" is all wet [Letters]. Ninety years of trying to do what he suggests—educating food employees and the general public about controls such as avoiding cross-contamination and thorough cooking—resulted in continuously increasing rates of foodborne disease. It was only after the Clinton administration imposed HACCP (hazard analysis and critical control point monitoring), pathogen reduction and end-product testing at the producer level that any reduction occurred.

JIM HARTMAN
Columbus, Ohio

PROPERTIES AT THE MESOSCALE may be discovered using novel nanotech devices such as these nanoelectromechanical resonators.



M. J. MURPHY, D. A. HARRINGTON AND M. L. ROUKES *California Institute of Technology*; COLORIZATION BY FELICE FRANKEL

ERRATA On page 41 of "The Art of Building Small," by George M. Whitesides and J. Christopher Love, an illustration describes conventional photolithography; in step 3, the lens is incorrectly labeled "mask," and the mask is unlabeled.

Nanoshells were invented by Naomi J. Halas with principal collaborator Jennifer L. West, both at Rice University ["Less Is More in Medicine," by A. Paul Alivisatos].

Transistor Arguments ▪ Canal Questions ▪ Medicine Prejudices

JANUARY 1952

AN UNHAPPY READER—"Sirs, the article in August 1951, by Louis N. Ridenour, properly entitled 'A Revolution in Electronics,' is most interesting. The article, however, conveys an entirely erroneous impression: that the three-electrode tube amplifier has virtually come to the end of its career. Dr. Ridenour neglected to mention the frequency limitations of the transistor. Under such limitations, it cannot begin to compete with the three-electrode tube, or audion, as I first styled it. The general application of the transistor in radio and television receivers is far in the future. —Lee deForest"

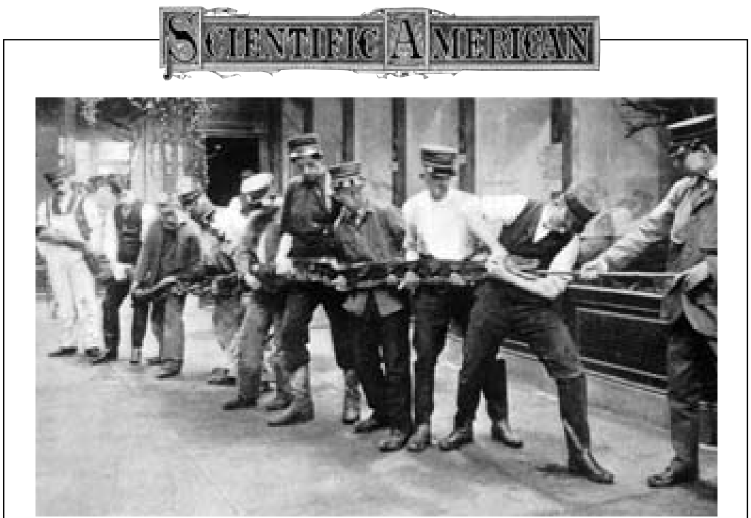
RIDENOUR REPLIES—"Sirs, I am very pleased to have the comments of the man who made possible the present age of electronics, even though I must take mild issue with some of them. The time at which consumer radio and television equipment can use transistors may indeed be some years off, as Mr. deForest says. However, this delay is likely to be due to the inability of rising transistor production to keep up with vast and growing military demands. The principal limitations of complex electronic apparatus are traceable to the fundamental shortcomings of the vacuum tube, which nearly half a century of development has alleviated, but not cured. —Louis N. Ridenour"

POISONOUS POULTRY?—"Antibiotics are shown to speed the growth of chicks and turkeys, and U.S. raisers are now feeding them to poultry on a large scale. Mortimer P. Starr and Donald M. Reynolds, bacteriologists at the University of California, examined intestines of turkeys grown on a diet supplemented with streptomycin and found that it took only three days for a bacteria population completely resistant to the drug to appear. If the feeding of antibiotics produces resistant varieties of parasites such as *Salmonella,* the organism may not only poison human consumers but be immune to treatment with drugs."

JANUARY 1902

PANAMA CANAL—"The report of the Isthmian Canal Commission has swept away from the whole canal question a mass of misconceptions and misstatements with which it has been hitherto clouded. Judged on the grounds of practicability of construction, security, permanence, convenience and ease of operation and cheapness of first cost and maintenance, the Panama Canal as designed by our engineers is by far the better scheme than the Nicaragua Canal. Congress has grown so used to considering Panama as a French undertaking that it is only now beginning to realize that if we take hold of the Panama scheme under our own terms of purchase, it becomes as truly an American enterprise as would the construction *de novo* of a canal at Nicaragua."

FEEDING A PYTHON—"Some time ago the New York Zoological Society secured a 26-foot python. It absolutely refused to eat anything, and while it is possible for a snake to refrain from food for a considerable period, there is an end even to the endurance of a snake. The authorities decided that extreme measures must be taken. The snake was firmly grasped by twelve men, and food, consisting of two rabbits and four guinea pigs, was pushed into its mouth by the aid of a pole [*see illustration*]. He was then put back into the cage to allow the processes of digestion to resume."



PYTHON being force-fed, 1902

JANUARY 1852

MEDICINES AND NOSTRUMS—"It is extremely common for dealers in quack medicines to advertise the same as being 'purely vegetable.' This is presuming upon the ignorance of the multitude. At one time, long ago, vegetable medicines, with the exception of alum and sulphur, were exclusively used. When science developed the virtues of mineral medicines, old prejudices were soon arrayed against the evils of the 'new drugs.' The same prejudices still exist in the minds of many, hence we hear of 'herb doctors' being the most safe. They believe that mineral medicines are more dangerous, but this is all sheer nonsense, for the most virulent poisons are extracted from herbs. Morphine, nux vomica, strychnia, nicotine and many other dreadful poisons are vegetable extracts."

news SCAN

BIOTERRORISM

Innocence Lost

IS ENOUGH BEING DONE TO KEEP BIOTECHNOLOGY OUT OF THE WRONG HANDS? BY W. WAYT GIBBS

In labs across the U.S. and Europe, dozens of geneticists are working to create stealthy viruses that can deliver artificially engineered payloads into cells without detection by the immune system. Other scientists have experimented with the influenza A pathogen and discovered that an infectious virus can be assembled from just eight short loops of DNA, easily synthesized by a machine. A year ago we would only have marveled at the ingenuity of such researchers, who after all are simply trying to perfect gene therapies for inherited diseases and to find new drugs for contagious illnesses.

DNA SEQUENCERS and other machines used in genetic engineering may be put under tighter controls to prevent their use in designing new types of bioweapons.

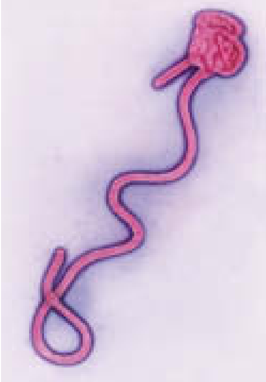
KAY CHERNUSH

Now, having witnessed the first attack with biological weapons against the U.S. government and media—albeit a clumsy and poorly aimed attack—biologists are more aware of the other edge of the swords they forge. With recipes for a vaccine and effective drugs in hand, the world can deal with anthrax and 11 more of the 50 naturally occurring bioagents that make the most likely weapons. Advances to come will probably offer some protection against the remaining 38 agents. At the moment, the defense has the advantage.

But biotechnology is quickly speeding up, shrinking down and automating the work of genetically engineering microorganisms. "You can now finish before lunch projects that used to consume a Ph.D. thesis," says Gigi Kwik, a fellow at Johns Hopkins University's Center for Civilian Biodefense Studies. Scientists joke darkly that it used to take a precocious high school student to make a bioweapon. Today, with the help of prepackaged kits and automated DNA synthesizers, the high school janitor can do it.

That is an exaggeration, thank goodness. But more could be done to forestall the day when miscreant engineers can create novel pathogens that resist antibiotics or that wreak havoc by tricking the immune system into attacking the body. A law passed in late October makes it a crime to possess "biological agents" except for research or medical uses. It also requires drug and background checks on lab workers who handle certain lethal microbes. Follow-on bills moving through the House and Senate would force everyone working with such germs or toxins to register with the federal government.

"We don't have a good handle on what pathogens are where," says Amy E. Smithson, a bioterrorism expert at the Henry L. Stimson Center in Washington, D.C. "Those regulations should be in place worldwide," Smithson says. But she notes that after the



EBOLA VIRUS could undergo genetic manipulation to enhance its already highly potent lethality.

U.S. tightened its controls on the shipment of dangerous pathogens several years ago, only the U.K. and Germany followed suit.

"Are the safeguards in place appropriate? So far I believe they are," says Carl Feldbaum, president of the Washington-based Biotechnology Industry Organization. "But are they sufficient? Probably not. I think we need to start thinking now about controlling the availability and export of those types of new instruments that could make it possible for a novice to create a dangerous biological agent."

Every year the military's Defense Threat Reduction Agency reviews about 25,000 export license applications to check that no equipment or materials are sent to places where they would likely be used to make advanced weapons. The list of restricted items runs 326 pages—but just four of those pages contain items used in the construction of biological weapons. The U.S. Customs Service has seized no illegal shipments of bioweapons components within the past 15 years, according to a spokesperson.

A few violations have been caught after the fact. Allergan, a biotech firm in Irvine, Calif., paid a settlement of $824,000 in 1998 after the government accused it of making 412 shipments of botulinum toxin to customers all over the world, including some in Saudi Arabia, Iran and Lebanon. But no special license is required to export DNA synthesizers and sequencers and other automated machines that can make it much easier to engage in the genetic engineering of microorganisms. Applied Biosystems, the leading vendor of such equipment, has its headquarters in California but branch offices in Indonesia, Malaysia, the Philippines, Saudi Arabia and 60 other countries.

That doesn't necessarily mean that wealthy, determined terrorists could whip up a batch of lethal vaccine-resistant bacteria without killing themselves. Keep in mind, Smithson urges, that "the Soviet bioweapons program was humongous: tens of thousands of scientists in dozens of research institutes were dedicated to this over decades." And its operation was exposed when an anthrax outbreak at Sverdlovsk resulted in nearly 70 deaths.

Feldbaum says that biotech industry leaders are already talking with government officials about restricting the export of some high-tech equipment. But it is far less likely that certain biological research will be classified in the way that much nuclear research has been. "We just don't think that top-down, command-and-control-style regulation of scientists will work," Kwik says. "Academics would fight it tooth and nail, and who can blame them? But perhaps scientists could self-govern" in ways that keep terrorists out of the loop.

CAMR/B. DOWSETT *Photo Researchers, Inc.*

A FELONY AGAINST US ALL

Richard Butler, who led the U.N. effort to destroy Iraq's biological munitions, suggested at a conference in November 2000 that the best way to prevent a bioweapons arms race is to strengthen international sanctions against them. "The possession of biological weapons—or actions unambiguously designed to produce them—should be categorized as a crime against humanity," he entreated.

AIR SECURITY

Lockerbie Insurance

HARDENED LUGGAGE CONTAINERS CAN NEUTRALIZE EXPLOSIVES BY DAVID McMULLIN

After a bomb went off in 1988 on Pan Am flight 103 over Lockerbie, Scotland, killing all 259 passengers onboard, the Federal Aviation Administration created standards that industry would have to meet if it chooses to deploy luggage containers capable of withstanding such a blast. During the 1990s, the FAA tested 10 hardened luggage containers made from a variety of materials, including reinforced aluminum, fiberglass, aramid fibers and polymers.

Only one container—concocted from fiber-metal laminates developed originally by the Delft University of Technology in the Netherlands—passed the FAA's test and received certification. The material, called Glare (short for *gla*ss *re*inforced), consists of multiple aluminum layers interspersed with layers of fiberglass and adhesive bonding that are supple yet strong. When used in fabricat-


EXPLOSION causes a luggage container made from a composite material called Glare to deform without breaching.

ED WEINSTEIN *Galaxy Aviation Security*

ing luggage containers, Glare can absorb bomb blasts without breaching. (One other container made of a different material passed the FAA test recently but has yet to be certified.)

To receive FAA certification for use in aircraft, hardened containers—loaded with luggage and placed in a plane's cargo bay during testing—must be able to withstand a blast "significantly more powerful than the Lockerbie bomb without damaging the aircraft's structure or impairing its flight-control system," says Howard Fleischer of the FAA's aviation security research department. During an explosion, Glare's multiple fiberglass and aluminium layers provide greater strength than aluminum alone.

As Glare expands with the blast, it absorbs the explosive energy and redistributes the impact load to the adjacent surface area rather than to one specific weak spot. The bomb blast leaves a sizable deformation in the container's surface, but it remains intact. Moreover, whereas other FAA-tested containers were also able to contain the bomb blast, Glare, whose glass fibers boast a melting point of 1,500 degrees Celsius, could resist the subsequent luggage-fueled fire inside the container. The post-blast fire melts Glare's innermost aluminum layer, but in doing so the underlying adhesive bond carbonizes, keeping the fiberglass layers in place and effectively forming a fire wall that prevents the container from collapsing.

The Explosive Containment System^3 (Ecos^3) container that incorporates Glare—designed by Galaxy Aviation Security in Egg Harbor Township, N.J.—is 150 pounds heavier than standard aluminum luggage containers. Because extra weight means lower profits, aluminum luggage containers remain the industry standard.

But perhaps not for long. Bill Evancho of Aviation Equipment in North Hollywood, Calif., the company that manufactures and sells Ecos^3 containers worldwide, reports a surge in interest in the material since the attacks on New York City and Washington. Evancho believes that Glare-hardened containers should be used for small bags, which are difficult and expensive to scan with x-rays.

The FAA is contemplating additional security regulations, and Glare may be an important material in this overall effort to fortify aircraft—and not just their luggage. It could serve, for instance, as a backing plate for the blast-proof and bulletproof cockpit doors that will be required on all commercial aircraft. Hardening airplanes alone won't prevent hijackings or another Lockerbie, but it will make it harder for terrorists to succeed.

David McMullin is a writer based in Delft, the Netherlands.

MORE THAN JUST BOMBPROOFING

The new Airbus A380 superjumbo jet (which seats 550 passengers and is scheduled for launch in 2006) will use Glare for the fuselage and also perhaps for the wings, bulkheads and floors. Glare is ideal for supersonic and jumbo jet aircraft construction because it has better impact, fatigue, corrosion and heat-resistant qualities than aluminum and can be made into large sheets.

Glare is considered suitable for any application where a strong and relatively lightweight material is desirable. It may be fashioned into windmill blades, the hull of a high-speed boat, or a police shield.

EVOLUTION

Taking Wing

A NEW VIEW OF THE ORIGIN OF BIRD FLIGHT EMERGES **BY KATE WONG**

BOZEMAN, MONT.—It's not often that a presentation given to the Society of Vertebrate Paleontology elicits coos and clucks of sympathy. These are, after all, the scientists who study *Tyrannosaurus rex* and other fearsome beasts of the past. But that's exactly the reaction Kenneth Dial got when, at the group's annual meeting last October, he showed video footage of a fuzzy little partridge chick with its wings taped to its sides trying to climb a tree—only to tumble down into Dial's waiting hands. Unfettered, however, the chick flapped its tiny wings while climbing and steadily made its way up. After teasing the audience for its sentimental display, the University of Mon-

WINGING IT: Ground birds often seek out trees and other elevated spots for safety. Juveniles not yet capable of flight accomplish this by running up the inclines, flapping their wings to enhance traction. The way these birds employ their developing wings may demonstrate the process by which avian flight evolved.

tana biologist returned to the matter at hand: explaining how this and other experiments involving ground-dwelling birds led him to hatch a new hypothesis regarding the origin of avian flight.

Traditionally, scholars have advanced two theories for how bird flight evolved. One of these, dubbed the arboreal model, holds that it developed in a tree-dwelling ancestor that was built for gliding but started flapping to extend its air time. The other, known as the cursorial theory, posits that flight arose in small, bipedal terrestrial theropod dinosaurs that sped along the ground with arms outstretched and leaped into the air while pursuing prey or evading predators. Feathers on their forelimbs enhanced lift, thereby allowing the creatures to take wing.

As the idea that birds descended from dinosaurs gained acceptance by all but a few paleontologists, so too did the cursorial hypothesis. But both the arboreal and the cursorial scenarios have explanatory gaps. As far as tree dwellers go, of the hundreds of nonavian gliding vertebrates around today, not one flaps its appendages. And why would natural selection have favored the development of little protowings in a theropod equipped with heavily muscled legs for running across the ground? Neither theory, Dial asserts, adequately addresses the step-by-step adaptations that led to fully developed flight mechanics.

Dial's eureka moment came after learning that partridges and their fellow ground birds routinely abandon terra firma in favor of trees and other elevated spots for safety. Although these animals appear to fly up into trees, he found on closer inspection that in many cases they were actually running up—legs bent and body pitched toward the tree—while flapping their wings. Subsequent research revealed that wing flapping assists in this vertical running by sticking the bird to the side of the tree, much as a spoiler helps to press a race car to a track.

Although the adult ground birds are generally perfectly capable of flying up trees, their preference for running may stem from a time early in life when they couldn't yet fly: before a baby ground bird has the ability to launch itself into the air, the only means it has for getting off the ground is vertical running. And as Dial's experiments show, when a juvenile is trying to evade a predator this way, the aid of even a partially formed wing can mean the difference between life and death.

Perhaps a bird ancestor's protowing conferred the same benefit, he suggests, and therefore natural selection favored its development. Over time, wings evolved to the point of enabling not only vertical running but, when employed by an animal running across the ground, flight.

So far Dial's model has ruffled few feathers. Living animals do not necessarily make good models of extinct ones, however. "Is that the way bird ancestors did it? Well, maybe, maybe not," comments Kevin Padian of the University of California at Berkeley. "But [Dial] is showing that it's possible." For his part, Dial is leaving it to the paleontologists to figure out whether his theory of the genesis of avian flight jibes with future fossil finds—or whether it's for the birds.

JANA BRENNING

ARTIFICIAL INTELLIGENCE

The World in a Box

LITTLE FANFARE GREETS THE COMING OUT OF A PIVOTAL AI PROJECT BY LAMONT WOOD

Twelve years ago artificial-intelligence pioneer Doug Lenat predicted that virtually all software in the 21st century would incorporate common sense about the world. At the time, Lenat was six years into a project called Cyc (derived from the word "encyclopedia") that was intended to fulfill his predictions. Now, after spending $50 million and with the 21st century upon us, Lenat has begun to roll out the first and still the only software that purports to be a database that can understand language by employing common sense.

It would have taken a single programmer 500 years to incorporate the almost 1.5 million facts about the everyday world that are in Cyc's database. Still, Cyc is clearly not HAL, the cybernetic protagonist of the Stanley Kubrick and Arthur C. Clarke masterwork whose namesake year has come and gone with computers eliciting not invigorating repartee but muffled cursing from their users at the obtuseness of their behavior.

Cyc's most prominent role thus far is as a software utility that improves the quality of retrievals for the Lycos Web search engine. If you search for "dime," it will suggest "Franklin Roosevelt" as an alternative topic, because Cyc knows that F.D.R.'s picture is on the dime.

That is impressive. But Lenat had expected a lot more progress toward commonsense software by now. In 1991 he told Scientific American that by the middle of the past decade the software code would be able to obtain new knowledge merely by reading—absorbing information from scanning raw blocks of text—rather than having software engineers feed it information in a programmed routine in which it asks question after question. Lenat had originally planned that Cyc would have had by now, at least, sophisticated natural-language interfaces through which it could learn new things by holding a free-flowing and unregimented conversation. But today Lenat says that will take another five years. As for turning Cyc loose on textbooks without constant hand-holding, that may take another 20 years.

The project got bogged down by the growing realization that facts alone are not enough: they require context. For instance, vampires are not real—but in fictional settings they may be treated as real. This inflated the size of the necessary database by a factor of 10, Lenat explains. Moreover, Cyc had to take in work to pay its bills. The project started life in 1984 as the brainchild of (former Central Intelligence Agency deputy director) Bobby Ray Inman's government-sponsored MCC (Microelectronics and Computer Technology Corporation) research consortium, to counter a then ominous Japanese effort in AI, the "fifth-generation" project. But even before the Cyc project was spun off (to create Cycorp) by the now defunct MCC in 1994, it had to depend on custom database projects for revenue.

Watching Cyc at work with a prototype natural-language interface is like watching a chat-room session with a tirelessly polite but ruthlessly inquisitive version of Helen Keller. Suppose you tell it that "*Bacillus anthracis* causes anthrax in people." It accepts that but then begins the process of "disambiguation." Do you mean anthrax the disease or the heavy metal band? Do you mean *People* magazine or members of the genus *Homo*? Seeing that the context is disease—using a system of logic called second-order predicate calculus—it infers that "causes" means "generates cases of" and not one of the other 19 definitions it recognizes for the word "causes."

The present database, Lenat suggests, offers enough power to make any software application that it interfaces with less likely to fall flat when confronted with the real world. Cycorp is preparing to release CycSecure, a network security system that contains information about the vulnerabilities of software and network configurations (it will understand, for instance, the need to watch out for disgruntled ex-employees), and OpenCyc, a freeware version of the database intended to encourage the rest of the world to cram real-world facts into Cyc.

The project may also be remembered for a demo tape of Cyc's natural-language interface, done for the Pentagon and dated April 2000. The tape showed an operator feeding Cyc information about an anthrax-like bioweapon and then proceeding to ask a series of questions about it. Cyc deduced that burning was a bad way to go about destroying a bacterium and that aerosols would be a poor way to spread it. And it also revealed that someone named Osama bin Laden did have access to it, because he controlled its possessor, an organization called Al Qaeda. Simple common sense for a CIA analyst—but it took almost two decades to teach it to a machine.

Lamont Wood is a writer based in San Antonio, Tex.

PURSUING HIS DREAM, Doug Lenat continues the quest for software that incorporates common sense.

DAN COHEN

AN ENTITY NAMED MONICA

The material in Cyc's database is expressed in second-order predicate calculus (a system of formal mathematical logic) using Cycorp's in-house notation, called CycL. A random line from the Cyc database, in CycL, reads:

```
(holdsIn   (YearFn 1998)
     (embarrassed BillClinton
          (sexualPartner
            MonicaLewinsky
            BillClinton)))
```

In English, it means: "In the time frame of 1998 it holds true that the entity named Bill Clinton was linked to the concept of embarrassment as a result of being linked to the sexual-partner concept involving the entity named Monica Lewinsky."

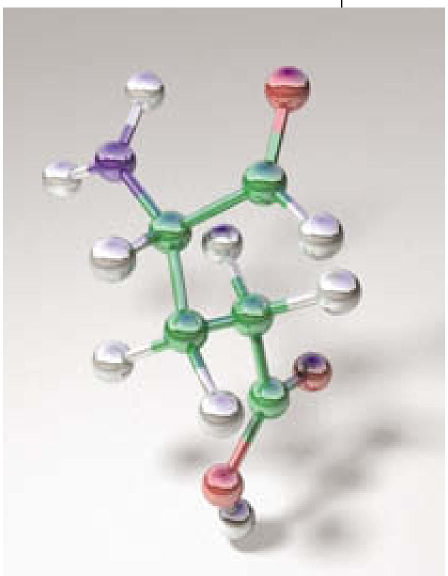
news SCAN

MEDICINE

Beating Abuse

GLUTAMATE MAY HOLD A KEY TO DRUG ADDICTION **BY TABITHA M. POWLEDGE**

Addiction has long been thought to be a form of learning. In the past few years, molecular biologists have amassed chemical evidence to prove it, in the process generating new ideas for combating drug use.



GLUTAMATE is a brain-signaling molecule involved in addiction.

Some of the most striking recent studies have examined the affinity between cocaine and glutamate, one of several chemical neurotransmitters that govern communication between nerve cells and are involved particularly with memory. For example, Stanislav R. Vorel and his colleagues at the Albert Einstein College of Medicine discovered that electrically stimulating the hippocampus, a brain structure central to memory and rich in glutamate, causes dependence relapse in rats formerly addicted to cocaine. Other researchers found that glutamate activates brain cells devoted to dopamine, a neurotransmitter associated with feelings of reward and pleasure. Indeed, the dopamine reward circuit in the brain has been regarded as the addiction pathway, commandeered not just by cocaine but by all addictive drugs. The fact that glutamate modifies dopamine action demonstrates a direct connection between brain reward circuits and those for learning and memory.

The reward and memory systems may harbor the secrets to addiction, but they also serve as a barrier to developing treatments. Altering either of these fundamental brain circuits without subverting some essential function is tricky business. "That's why there was excitement about the possibility that the glutamate system might be involved. But at this point, we're not there," says Francis J. White, a pharmacologist at Finch University of Health Sciences/The Chicago Medical School.

A discovery published in September 2001 may nudge that process along. Researchers studying mice identified a particular glutamate receptor, known as mGluR5, that is crucial for cocaine dependence. Mice that lack the receptor do not become dependent no matter how much cocaine they are given. The mGluR5 findings are significant in part because the receptor's action appears to be selective. The mutant mouse takes food and water just like other mice, which suggests that lack of the receptor does not affect "natural" rewards, only interest in cocaine.

Eliot Gardner, a senior research investigator at the National Institute on Drug Abuse, identifies two major hurdles to basing addiction treatments on glutamate. The first is figuring out which glutamate receptors are involved. (Even if mGluR5 is related to human cocaine dependence, it is not the only receptor significant in addiction.) The second problem is glutamate's ubiquity. "It's found all over the brain in lots of circuits subserving lots of behavior and mental processes that one would not want to manipulate," Gardner says. Researchers will need to find precise delivery systems that will target only specific brain circuits, leaving alone the dozens, or perhaps hundreds, of other circuits that use glutamate as a neurotransmitter.

Intriguingly, the glutamate studies could strengthen that old nonpharmaceutical standby: behavioral therapy. One of the most promising treatments "is to have people unlearn aspects of addiction and relearn new things to do in life," says renowned molecular biologist and addiction specialist Eric J. Nestler of the University of Texas Southwestern Medical Center. "An argument can be made that Alcoholics Anonymous provides that type of alternative focus."

Or pharmacotherapies could be combined with "talking cures" to yield fewer relapses. "If we could develop medications that could address the underlying biology, the powerful biological forces that drive addiction, then we can make a person more amenable to other treatments," such as behavior therapy, Nestler says. "You really need both."

Tabitha M. Powledge is a science writer who specializes in biology.

DRUGS FOR DRUG ABUSE

The hunt for addiction treatments grows more intense every year. The National Institute on Drug Abuse is conducting clinical tests on more than 60 compounds for cocaine and opiate dependence alone and also a few for methamphetamine, according to Francis Vocci, who directs NIDA's Division of Treatment Research and Development. In addition to some compounds that act on glutamate and dopamine, researchers are looking at other targets. Chemicals that block the action of stress hormones are effective against opiates, cocaine, amphetamines and alcohol, Vocci reports, which means that a magic bullet that works against mechanisms underlying all addictive drugs is not utterly out of the question.

BRYAN CHRISTIE

PHYSICS

Fractional Success

A NEW THEORY OF EVERYTHING? PROBABLY NOT BY GRAHAM P. COLLINS

Strange things happen to electrons when they are confined to a thin layer of semiconductor, cooled to near absolute zero and subjected to a high magnetic field. Instead of behaving as independent particles, they act collectively to form entities called quasiparticles, which have counterintuitive properties such as fractional charges. The physics of this quantum-electronic flatland is known as the fractional quantum Hall effect and has been an extremely fertile area for experimenters and theorists alike. But nothing quite like this system has ever existed—even as a theory—in more than two dimensions. Now two physicists have generalized the two-dimensional theory to four dimensions, and to cap it off they have made a controversial conjecture that the result could have relevance for fundamental particle physics and quantum theories of gravity.

Shou-Cheng Zhang of Stanford University and his student Jiangping Hu worked out a four-dimensional version of a quantum Hall system that would exist on the surface of a sphere in five dimensions. The key idea for the new theory came to Zhang one hot summer day in 2000 while he was lecturing at Tsinghua University in China, with which he and Hu are also affiliated. The higher-dimensional sphere was already familiar to Zhang and his students; in 1996 he developed a theory of high-temperature superconductivity based on its symmetries. According to Robert B. Laughlin, also at Stanford and recipient of the 1998 Nobel Prize in Physics for devising the original theory of the two-dimensional fractional quantum Hall effect, "the discovery of the four-dimensional quantum Hall state is rather beautiful and a real breakthrough. I tried for years to do something similar with little success."

At the outer limits of the two-dimensional system, the quasiparticles generate quantum objects called edge states, somewhat like waves rippling around the perimeter. Analogous states occur at the boundary of the four-dimensional system, but that boundary is three-dimensional, just like the universe we know and love. In their paper, published in the October 26 *Science*, Zhang and Hu propose that some of these three-dimensional edge states have properties similar to photons, gravitons and other fundamental particles of our world. That result would open a new route to a quantum theory of gravity, one that would seem to be very unlike existing quantum-gravity theories, which invoke superstrings, higher-dimensional "branes" and quantum loops. The appearance of the edge states with the claimed properties is called emergent relativity, because the particles emerge from the theory and also obey Einsteinian relativity without taking that requirement as an assumption that must be deliberately incorporated in the underlying equations, as is usually the case.

QUANTUM FLATLAND boosted to four dimensions hints at a unified theory.

SAMUEL VELASCO

Few experts are persuaded by these larger conjectures about the four-dimensional quantum Hall system. Frank Wilczek of the Massachusetts Institute of Technology, a distinguished theorist whose work has run the gamut from particle physics to exotic condensed matter such as the quantum Hall system, says that the proposal to build world models from the theory "requires a big leap of faith." The correct interactions between the gravitons and other particles must also emerge, and he is skeptical that that will happen, because nothing like it occurs in the two-dimensional system.

Laughlin is more blunt. "The implicit claim of the paper—that they have found emergent relativity—is false," he asserts. The edge states in question involve pairs of the four-dimensional quasiparticles moving in synchrony, but the tiniest disturbance would break the pairs apart. Zhang agrees that the connection with relativity is still very preliminary and says that forthcoming papers will address some of the objections. For the moment, then, the theory is ingenious mathematics—but of the type that has a long history of ultimately finding use in real physics.

MATHEMATICS AND THE UNIVERSE

The mathematical structure of the new four-dimensional theory is deeply related to quaternions, a number system in which negative one has three different independent square roots (one such square root generates complex numbers). Only quaternions, complex numbers and real numbers—corresponding to four, two and one dimensions, respectively—have the right properties for making the required exotic quantum state.

Elementary particle physics and condensed-matter theory (which covers the behavior of materials such as semiconductors and phenomena such as the quantum Hall effect) have many surprising similarities. For example, the theory of superconductivity is closely related to the phenomenon of confinement of quarks inside protons and neutrons and also to the theoretical Higgs field that causes particles to have mass. It is as if empty space behaves like a vast piece of superconducting metal.

news SCAN

DATA POINTS: ZAPPED

Average annual radiation exposure for a U.S. resident: 3.6 millisieverts (mSv)

Radiation from:

- **Radon:** 2 mSv
- **Food and drinking water:** 0.4 mSv
- **Diagnostic x-rays:** 0.4 mSv
- **Cosmic rays (at sea level):** 0.26 mSv
- **Flying from New York to Hong Kong:** 0.1 mSv

Maximum permissible occupational exposure per year: 50 mSv

For pregnant women: 5 mSv

Annual exposure from watching television: 0.01 mSv

Loss to life expectancy: 1.5 minutes

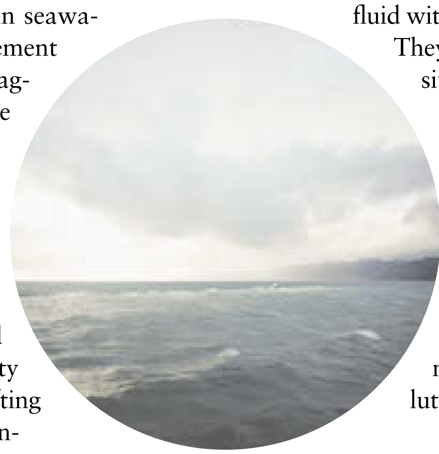
Equivalence in cigarette smoking: fewer than 2 puffs

SOURCES: Federal Aviation Administration online calculator, http://jag.cami.jccbi.gov./; Environmental Protection Agency; Occupational Health and Safety Administration; National Council on Radiation Protection and Measurements; Centers for Disease Control and Prevention. New York–Hong Kong radiation exposure calculated assuming flight at 41,000 feet for 15.5 hours in July 2001; realistically, the exposure will be less (1 millisievert = 100 millirems).

GEOLOGY

A Sea Change

One long-held belief about ocean chemistry is that it never changes. A newer theory proposes that changes in seawater occur with the movement of tectonic plates: the magma released when the plates move apart absorbs magnesium, releases calcium, and thereby alters seawater. Now chemists and geologists from Binghamton University and Johns Hopkins University have found proof of shifting ocean chemistry in ancient salt deposits. They collected sea crystals from around the world that contained densely packed drops of water and examined the fluid with an electron microscope. They found that the magnesium-calcium ratio was the same all over the earth at any given time but varied from time to time during the past 600 million years. That change, the researchers surmise in the November 2, 2001, *Science*, may have affected the evolution of various marine organisms, such as algae, corals and sponges. *—Diane Martindale*



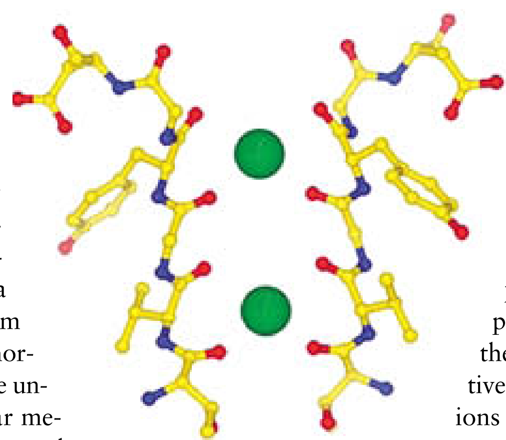
OCEAN CHEMISTRY does not remain static.

BIOLOGY

Channel Crossings

For decades, biologists have wondered how ion channels—proteins that span cell membranes and allow charged molecules to pass through—let the ions move so fast yet can be so selective at the same time. Now two teams—one at the Rockefeller University, the other at Cornell University and the University of Montreal—studying potassium channels, which play a role in everything from nerve signals to hormone secretions, have unraveled the molecular mechanics of these minuscule protein pores and explained why ion channels are so efficient. High-resolution three-dimensional snapshots of the channels in action revealed how individual potassium ions pass through them. They show that the ions occupy one of seven spots inside a channel, four of which let in only potassium ions; the others facilitate movement into the cell. The ions pass through the pore, moving from one of the selected places to another as more ions push them through from behind.

A series of experiments that measured the electrical oscillations across the channel allowed the group to make a determination of how much energy the potassium ions need to jump from place to place. It turns out that the channels are so selective for potassium that the ions require almost no energy to pass through, thereby excluding other ions, such as sodium. The discovery will help scientists better understand the genetic and biochemical abnormalities that affect the body's ion channel proteins and may assist in future drug design. The work appears in three papers in the November 1, 2001, *Nature*. *—Diane Martindale*



POTASSIUM IONS traverse part of a cellular channel.

JOHN K. HUMBLE *Stone* (*top*); © 2001 *NATURE*, RODERICK MacKINNON ET AL. (*bottom*); ILLUSTRATION BY MATT COLLINS

DISASTER RELIEF

Political Watershed

FLOOD AID rises every four years.

Politics seems to be partly responsible for opening the floodgates to federal disaster relief money. Looking back over disaster declarations and expenditures for the years 1965 to 1997, researchers at the National Center for Atmospheric Research found that presidents were 46 percent more likely to declare flood-related disasters during presidential campaign years, whether or not the flooding and rains were severe. Even when states were able to provide adequate flood relief on their own, a high level of flood damage tended to trigger a disaster declaration that brought federal aid. Aid provided too readily could leave states with less incentive to prepare for flooding, the authors noted. All else being equal, Presidents Johnson and Reagan were the most tightfisted, whereas Nixon, the elder Bush and Clinton were comparatively generous. The researchers, whose study appeared in November's *Natural Hazards Review,* suggested that clearer guidelines for defining a disaster could help reverse the recent surge in federal spending on flood relief. —*JR Minkel*

ASTRONOMY

Swirling Dust

GALACTIC DUST obscures the microwave background.

In the past year modern cosmologists have confirmed that spacetime is flat—a seemingly simple statement that hides a tortuous analysis of the cosmic microwave background radiation. The background is crusted over with "foregrounds" emitted by interstellar dust and gas; in only a few areas of the sky can cosmologists make clean measurements. Now a group led by Douglas P. Finkbeiner of Princeton University has scrubbed away a bit more of the muck. At far-infrared wavelengths, the foreground is primarily thermal emission from dust; at radio wavelengths, plasma emission dominates; in between is a "Foreground X," which has puzzled researchers for years. Finkbeiner's group has found the first direct evidence that spinning, 10-nanometer dust grains are to blame. "When the grains are hit by ions, they immediately start to rotate, and then they release their energy," says fellow dust-buster Angélica de Oliveira-Costa of the University of Pennsylvania. Having identified this novel type of emission, observers should be able to compensate for it and thus clear away much of the lingering uncertainty in cosmological measurements. —*George Musser*

ECOLOGY

Warmed-Up Genes

While debates about the existence of global warming continue, mosquitoes may have the proof in their genes. William E. Bradshaw and Christina M. Holzapfel, ecologists at the University of Oregon, discovered that the North American pitcher-plant mosquito, *Wyeomyia smithii,* which uses shortening day length to judge when to hole up for the winter, is now hibernating later as winters get warmer. Mosquitoes are waiting nine days longer than their ancestors did in 1972. Over the past 30 years Bradshaw and Holzapfel have caught wild mosquitoes and tested them under identical artificial-light conditions to show that the insects' response to day length has changed in as little as five years. This is the first genetic adaptation to global warming to be identified. Animals with a less flexible genetic response could face extinction, the researchers concluded in the November 6, 2001, *Proceedings of the National Academy of Sciences.* —*Diane Martindale*

CHARLIE RIEDEL *AP Photo (top)*; DAVID J. SCHLEGEL AND DOUGLAS P. FINKBEINER *Princeton University* AND MARC DAVIS *University of California, Berkeley (bottom)*

WWW.SCIAM.COM/NEWS

BRIEF BITS

- Scientists have coaxed tiny metal particles to self-assemble into microscopic wires that conduct electricity and repair themselves, research findings that may be useful in creating circuits in wet environments, including inside the body. /110501/1.html
- Human sweat contains an antimicrobial protein that acts against a wide range of pathogenic organisms, among them *Escherichia coli* and *Staphylococcus aureus.* /110501/2.html
- Imaging of nearby galaxy M87's core reveals that the black hole residing there has either a nonexistent or much fainter ring of dust around it compared with other active galaxies. Scientists had thought that these rings were key features of such highly energetic galaxies. /110101/1.html
- Three successive mammoth species (the last of which was the woolly variety) evolved advanced features in Siberia, which later propagated to Europe. A number of these changes represented adaptations to grazing in Siberia's periglacial conditions. /110201/1.html

news
SCAN

BY THE NUMBERS

Going Solo

UNWED MOTHERHOOD IN INDUSTRIAL NATIONS RISES **BY RODGER DOYLE**

Forty years ago unmarried mothers accounted for only 5 percent of births in western Europe and English-speaking countries; today that proportion is about 30 percent. The increase has been accompanied by the spread of cohabitation, more so in Europe than in the U.S., and indeed in some regions, such as Scandinavia, the distinction between legal marriage and cohabitation has been fading.

The causes of this historic development are even now not fully understood, at least in its American manifestation, but increased sexual permissiveness beginning after World War II is surely involved. Also among the developments that may have contributed to the rise in unwed motherhood in the U.S. is the loss, beginning in the 1960s, of relatively unskilled but well-paying manufacturing jobs. In working-class neighborhoods, young men capable of supporting a family became ever more scarce. Black men, who were just starting to participate in the industrial economy in the 1940s and 1950s, found it particularly difficult to get good jobs. Yet according to one estimate, the lack of decent jobs cannot explain more than a fifth of the nonmarital births among black Americans.

A second development may have magnified nonmarital births—the growing number of women who are financially independent and thus able to have children on their own. But the evidence suggests that single mothers by choice are, at best, a minor contributor to the out-of-wedlock trend. Other explanations, such as the growth of welfare, are not well supported by research.

Some unmarried women who became mothers did not use contraceptives, and many who did found them ineffective. The Pill and condoms have failure rates of 9 and 15 percent, respectively, and among younger women, the unmarried and minorities, the rates are higher still. It is not surprising that 55 percent of all births among unmarried women and two thirds of those among teenagers, as noted in a 1994 U.S. survey, were unintended.

Compared with Canada and western Europe, the U.S. is in the middle range in births to unmarried women, but among adolescents U.S. rates are much higher [*see table at left*]. Teenage motherhood is particularly problematic because most girls lack parenting skills and don't have the resources to bring up children properly. In most western countries, but not the U.S., there is a strong consensus that adolescents should not bear children. American adolescents are less apt than those in other countries to use contraceptives and may not use them as effectively. Western Europeans and Canadians generally provide better access to family-planning programs for teenagers. In France, for example, nurses in public and parochial high schools dispense the "morning-after pill," a practice unheard of in the U.S.

In Japan, where nonmarital births are extremely rare, unwed mothers and their children are severely stigmatized, even to the point of denying them benefits available to married mothers. In Europe, countries with large Catholic populations tend to have fewer nonmarital births, although France is a major exception. In Scandinavia, a traditionally strong Protestant region, the rate of nonmarital childbearing is the highest in Europe.

Rodger Doyle can be reached at rdoyle2@adelphia.net

NEED TO KNOW: OUT OF WEDLOCK

Percent of all nonmarital births accounted for by women ages 15 to 19:

U.S.	29
Canada	15
Great Britain	15
Italy	10
Germany	9
France	4
Sweden	2

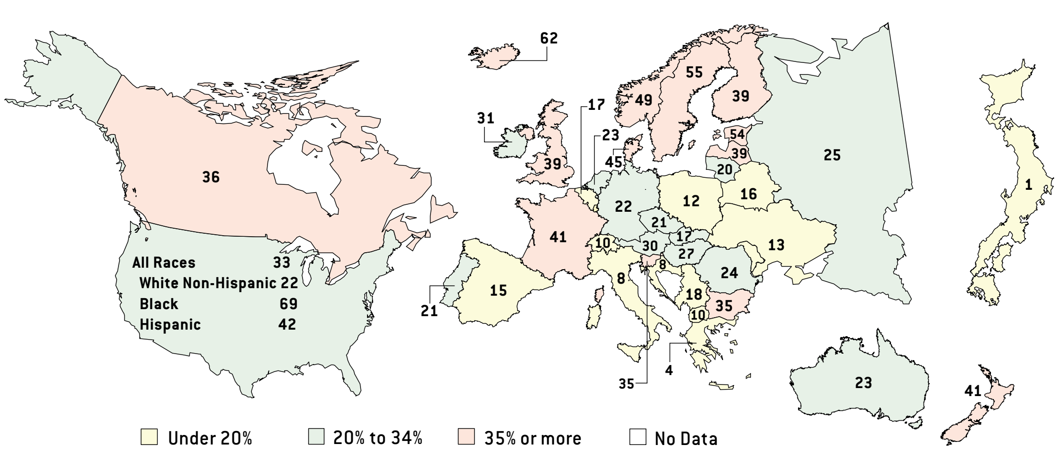
Data are for 1999, except for Canada and France, which are for 1998, and Italy, which are for 1996.

ON THE WEB: SINGLE MOTHERHOOD

Links to sites on unwed motherhood and a chart showing the nonmarital trends in the U.S. since 1940 can be seen at www.sciam.com/2002/0102issue/0102numbersbox1.html

SOURCE FOR MAP: Office for Official Publications of the European Communities. Data are for mid- to late 1990s, except for Japan, which are for 1990.

PERCENT OF BIRTHS OUTSIDE OF MARRIAGE



RODGER DOYLE

Mimicking Mother Nature

Marrying art and science, Nekton Research has developed an underwater robot inspired by a one-celled organism By JULIE WAKEFIELD

DURHAM, N.C.—"Right now you're the only person in the world who is holding five submarines in your hand at once," Charles Pell tells me. In my palm are five 70-gram robots the size of Havana cigars. Though toylike, they may be the world's smallest autonomous underwater vehicles (AUVs). They can turn on a dime and maintain a set course in open-water tests. Larger versions can cruise at speeds of up to three knots (1.5 meters per second) and maneuver sharply.

The bots, called MicroHunters, number among the latest creations hatched by Nekton Research, a technology incubator founded in 1994 to apply emerging ideas from the lab of Stephen A. Wainwright, a leader in the field of biomechanics. Wainwright's Bio-Design Studio was once part of Duke University's zoology department, where scientists and artists collaborated to build numerous three-dimensional working models of various biological organisms.

MICROHUNTERS are autonomous underwater vehicles that may one day carry sensors for environmental monitoring or defense.

Nekton has been riding a leading wave of biomimetics research, abstracting clues from Mother Nature's designs for use in robotics. Whereas reptiles and insects have inspired other robot designs, MicroHunter borrows from a far simpler creature: the single-celled paramecium. "It has just one single moving part," says Duke zoologist Hugh C. Crenshaw, a Nekton collaborator. Paramecia, he explains, move in a helical pattern, orienting themselves to external stimuli by shifting their rotational velocity. Unlike a car cruising down a highway, a helically traveling object doesn't follow its nose but spirals toward a target by changing its speed along its winding path.

Crenshaw deciphered the algorithm of the twisting motion, known as helical klinotaxis, and assisted Nekton's team in applying it to the robots, in essence crafting a new guidance technology. Driven by propellers, MicroHunters navigate in three dimensions by homing in on light sources, depth, pressure or a direction—magnetic north, for example.

"Our micro AUVs are changing the way people are thinking about doing oceanography," says Pell, a sculptor and biologist who is Nekton's co-founder and vice president of science and technology. Besides an M.F.A., his résumé includes everything from dissecting tunas to building dinosaur exhibits for the Smithsonian Institution's National Museum of Natural History. The AUVs are "basically platforms waiting for more sensors to be miniaturized," Pell says.

When packed with myriad sensors, abundant schools of aquabots will cheaply and efficiently augment data from satellites, ships and buoys. That is the hope, anyway, of Nekton's core creative group of biologists, ocean engineers, roboticists, physicists and mathematical modelers. The tiny submarines, currently rated to depths of 100 meters, will eventually perform 3-D mapping of water-column properties for research, industrial and military applications.

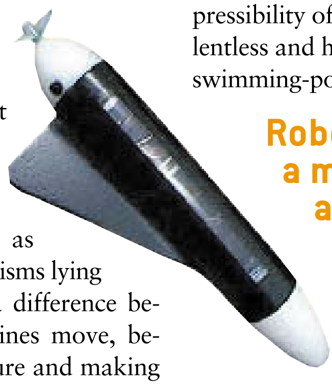
In battle arenas the tools, whose development was sponsored by the Defense Advanced Research Projects Agency, could be used to measure effluents from suspected chemical weapons factories, to help clear a harbor of mines, to detect trace plumes of pollutants, to screen water supplies, and even to wander up canals and irrigation ditches for intelligence gathering.

Ironically, Nekton was founded to manufacture a bathtub toy called TwiddleFish, basically a piece of

PHOTOGRAPHS COURTESY OF NEKTON RESEARCH

rubber fashioned in the shape of a fish that faithfully mimics its swimming motion. Pell stumbled on the design in January 1992 while making more complex 3-D working models of the locomotor systems of mackerel and tuna with Wainwright at the Bio-Design Studio. "It was stunning at first that something so superficially simple worked so well," Pell recalls. He, Wainwright and two business partners incorporated soon thereafter and licensed the discovery. Two versions, a clown fish and a great white shark, soon followed and are available at some museum and aquarium gift shops across the country.

Modeling has been central to the privately held company's process of innovation ever since. Nekton researchers build 3-D working models of biosystems by hand, employing kinesthetics (the ability to feel movements of the limbs and body) to aid in uncovering new notions about the way things move. And for Pell, who drew his first paramecium as a toddler, modeling has been a lifelong pursuit. During his years at art schools, his studio looked like an inventor's lab, with as many machine parts, tools and mechanisms lying around as sculptures. "I never saw a difference between the way organisms and machines move, between the activity of making a sculpture and making an aircraft," he says. As Pell sees it, what Nekton does is a blend of art and science.



In the case of MicroHunter, the team initially planned to test prototypes in a tank filled with six metric tons of clear silicon goop to approximate the viewpoint of a cruising microorganism. To a paramecium, swimming through water feels the way trudging through chilled molasses would feel to us. Before filling the tank, though, Nekton's engineers decided to try to tweak the algorithm to account for such effects as the inertia of less viscous media, like water, and so they plunged a prototype into a swimming pool. To copy the cell's orientation mechanism, Nekton's engineers also had to copy its feature of not caring which way is up, because the cell itself is not affected much by gravity. "We weren't even sure we could do it," says Jason Janét, Nekton's vice president of research and development.

After much tinkering, someone had the idea to switch the power on and off to turn the vehicle. It worked. Eventually the team achieved a pure-science solution in which the sub automatically and continuously tracks an external signal, much the way a paramecium orients itself to light or other signals, such as concentrations of chemicals in a fluid medium. Deliberately turning the propeller on and off at different positions in the helix proved to be a new control option. As a result, MicroHunter steers in two modes: one strictly biomimetic, the other derived from computer modeling of how the sub responds in water when the prop speed is changed. It was the latter mode "that allowed us to understand what was important about the dynamic [computer modeling] system," Pell says, "and to develop a basis for many other things that we've done since with other vehicles."

In designing its robots, Nekton tries to distill and program into the machines the essence of a biological organism's motion. In the case of the paramecium, MicroHunter emulates its sheer doggedness and irrepressibility of movement. Underwater, the bots are relentless and hard to detect. In half of six three-minute swimming-pool tests, a former U.S. Navy SEAL, playing underwater goalie, couldn't prevent most of a swarm of them from swimming past him to the beam of light that serves as a target.

Roboticists try to program into a machine the essence of a biological organism's motion.

MicroHunter itself probably will not be armed as a weapon for some time, if ever. For now, it's low on the intelligence scale as AUVs go. Just fitting sensors into the fuselage presents a problem—the control electronics supporting many desired sensors are bigger than the 70-gram platforms.

But MicroHunter's orientation effect is scalable, Pell says as he shows off (among others) an eight-centimeter-long, seven-gram test swimmer and a 30-centimeter-long, 700-gram version loaded with sensors that measure both acceleration and magnetism and other parameters in all three dimensions. New capabilities, such as remote programming of the robot's swimming instructions, are sure to follow soon. In time, the micro AUVs could be launched individually or in a flotilla to form a moving sensor array.

If Nekton's metal creations do succeed in ocean tests and become as capable in the sea as fish, another difficulty may arise: their size means that they might be mistaken as bait. That's a challenge Pell welcomes. SA

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

Extreme Medicine

In a hospital northeast of Kabul, surgeon Gino Strada is redefining what it means to provide quality medical care in a combat zone By MARCO CATTANEO AND SERGIO PISTOI

COURTESY OF EMERGENCY

GINO STRADA: WAR M.D.

- **Born in 1948 near Milan; married, with a daughter. His wife, Teresa, coordinates Emergency activities from the group's headquarters in Milan.**
- **Publication in 1999 of *Pappagalli Verdi* (*Green Parrots*), a nickname for a type of land mine. The account of Strada's experience as a war surgeon became a best-seller in Italy, with 110,000 copies sold.**
- **"If you set up a hospital in a Third World country, you have to build a place where you wouldn't mind having your children treated."**

IN LATE OCTOBER three Katyusha rockets, launched by the Taliban in retaliation for U.S. air strikes, hit the market of the small city of Charikar in territory controlled by the opposition Northern Alliance. Two people die in the attack, and another 25 are injured. The injured, all civilians, among them many women and children, are rushed along a bumpy road to Anabah, in the deep gorge of the Panjshir Valley. There, 60 kilometers from Kabul, is the only hospital in all of northern Afghanistan equipped with the accoutrements of modern medicine: an emergency room, a radiology suite, two fully outfitted operating theaters with a supply of oxygen, a clinical laboratory, sterilizers, a blood bank, an intensive care unit, and four surgical wards and beds for 70 patients.

In a country with scant electricity, phone service and running water, the hospital's neat, one-story white building appears almost as a mirage against the impressive backdrop of the Hindu Kush mountain range. On the side of the hospital are painted the three red stripes that represent the logo of the international aid organization Emergency, a nongovernmental agency headquartered in Milan, Italy.

The little hospital in Anabah does not go ignored by the rest of the world. A few hours later the figure of a rugged, slightly disheveled hulk of a man appears on Italian television. Gino Strada, the gray-bearded, 53-year-old chief surgeon at the Anabah hospital and the co-founder of Emergency, sorts the injured in preparation for their entry into the operating room. Strada has gained celebrity both in Afghanistan and in his native Italy, where he has been described as a *leggenda vivente* by the Turin daily newspaper *La Stampa*.

A onetime heart and lung transplant surgeon, Strada was groomed for the good life, with stints as a visiting surgeon at Stanford University and the University of Pittsburgh. That life was transformed forever in 1988, when Strada decided that he wanted to experience firsthand how medical care in the developing world is provided. A five-year assignment with the International Committee of the Red Cross (ICRC) took him to Afghanistan, Pakistan, Peru, Bosnia, Ethiopia, Djibouti and Somalia, as well as to Cambodian refugee camps in Thailand. Unimpressed with the quality of care furnished by the ICRC, Strada set off on his own. With help from his wife, Teresa, and a group of friends, Strada founded Emergency. The group is dedicated to providing medical help in world flash points that is comparable to the care Strada encountered in Milan and Palo Alto. Emergency's motto: "Life support for civilian war victims."

The Italian television spot about the Charikar rocket attacks—as with countless other broadcast and print stories throughout the years—is important to publicizing Emergency's mission. To date, the group has garnered about $16 million in six and a half years from private donors (including an Italian professional soccer team), the Italian Foreign Affairs Department and the European Commission Humanitarian Aid Office. Emergency's three red stripes can now be found on hospitals the organization runs in northern Iraq, Cambodia, Sierra Leone and elsewhere in Afghanistan.

Setting up hospitals in societies decimated by years of war requires skills that go beyond the intricacies of tying a suture. Emergency's work in Afghanistan illustrates the difficulties it encounters everywhere it goes. In 1999 Strada and his colleagues flew in a beat-up Soviet helicopter from Dushanbe in Tajikistan to northern Afghanistan and then traveled by truck to meet ousted Afghan president Burhanuddin Rabbani and the head of the opposition military forces, Ahmed Shah Massoud (who was assassinated September 9, 2001, by suicide bombers). The Northern Alliance leaders assented to the proposal to build the Anabah hospital. The need for such a facility was undeniable. An estimated 1.5 million troops and noncombatants have died in the more than two decades of Afghan strife, and in excess of two million soldiers and civilians have been maimed.

Strada and his Emergency co-workers rebuilt an abandoned police college—using wood from old Soviet ammunition boxes in the ceiling and pipes from military tanks for plumbing. Hospital equipment arrived after a 22-day trek by truck from Tajikistan. As constructed, the hospital is completely autonomous, housing its own electrical generators and even a playroom for children, who represent more than one third of the patients. It also staffed six first-aid posts along the Northern Alliance frontline and deployed six converted four-wheel-drives that provided ambulance service. The hospital, since it opened in December 1999, has already treated upward of 8,400 people, mostly civilian victims of land mines and bombs. Patient mortality stands at an enviable 3.5 percent. Since the beginning of the Anglo-American air strikes this past fall, Emergency has been one of the few international aid groups to have remained continuously in Afghanistan. And despite the conflict, Strada has not scrapped plans for expansion. "We are setting up new departments of obstetrics, pediatrics and eye surgery," he says.

Although Strada spearheaded the creation of Emergency, he has not sought to create a cult of personality. Other Emergency staffers in Afghanistan have shown every bit as much drive as Strada. In May, Kate Rowlands, the 45-year-old chain-smoking Welsh nurse who serves as the group's medical coordinator in Afghanistan, faced down officials from the Taliban's Ministry for Promotion of Virtue and Prevention who were brandishing Kalashnikov machine guns and leather whips. Nevertheless, the Taliban invaded Emergency's newly opened Kabul hospital and beat staffers with the whips because of alleged "promiscuity": the government charged that men and women were allowed to eat together. Later the Pashto-language government station, Radio Voice of Shari'ah, reported that the hospital "had appointed serving personnel in a self-willed manner without the understanding of the Ministry of Public Health and had violated all

LIKE A MIRAGE, the Emergency hospital nestles below the Hindu Kush mountain range.

MARCO CATTANEO AND JASMINA TRIFONI

laws and regulations by having a joint dining room."

The Kabul hospital was closed for months, although a few of the Afghan staff members there stayed to compile a list of civilian casualties from the bombings—a number that had reached more than 100 by early November. Strada is adamantly opposed to what he calls the U.S.'s cowboy-style intervention, which he believes will only hurt innocents. The hospital in Anabah, he says, has already treated three adults and four children, victims of an errant bomb dropped by U.S. forces. The current conflict, Strada declares, originates from previous neglect by the U.S. of its relations with Afghanistan, and the recent U.S. offensive will stoke the flames of fundamentalism, the repercussions of which will ultimately be felt by the West.

The Kabul hospital's doors remained shut, not because of the American bombings but rather because of the Taliban's refusal to guarantee the safety of the international staff. "The problem," Strada says, "was the threat by non-Afghan fighters from at least 20 different countries, including Al Qaeda people who were in the capital, who clearly vowed to kill all foreigners and infidels, both of which I definitely am." Even before Taliban rule in the capital crumbled in November, Strada had traveled to Kabul to make preparations to reopen the hospital.

SURGICAL TEAM of Strada (*left*) and a Kurdish surgeon tends to a patient in the Anabah hospital.

One of the goals of Emergency in Afghanistan—and in every other country where it maintains hospitals—is to put people like Strada and Rowlands out of a job. Strada and his colleagues teach local physicians, health care workers and administrators the skills needed to run a modern facility and in the end depart. The group's hospital and first-aid posts now provide jobs to more than 200 Afghans. (In fact, some of the doctors and nurses were Kurds who came to Anabah after having been trained in similar programs in northern Iraq.)

Emergency's rules are strict. The Kalashnikovs that many adult males carry are forbidden inside the hospital. Even the late military commander Massoud left his firearm at the door when he became one of the first visitors to the new facility. Female workers are not allowed to wear the head-to-toe covering called a burqa, and those involved in medical care receive daily lessons in English, medicine and hygiene.

People staffing the kitchens and maintenance jobs are often former patients who were seriously injured by land mines or shrapnel. "Employing them in the hospital is the only way to ensure their survival in Afghan society," Strada says. Using local employees and materials helps to keep costs down. "In Afghanistan, we do everything with less than $1 million, including international staff salaries and drug supplies," he notes.

Medical care cannot be separated from social aid programs in a country whose infrastructure has totally collapsed after 22 years of uninterrupted war. So the hospital has initiated social programs for widows and families and has constructed a small hydroelectric plant in the Panjshir Valley, bringing electricity to this area for the first time. "If the war turns out the lights, a simple lightbulb may be a little sign of peace," writes Strada in Italian in one of the frequent letters from Anabah that he posts regularly on Emergency's Web site (www.emergency.it).

The work of a wartime emergency physician always threatens to overwhelm. In 1996 Strada was managing Emergency's hospital in northern Iraq when Saddam Hussein's troops began attacking the Kurds. Working 18-hour days proved too much. He suffered a heart attack and had to undergo a quadruple bypass in Italy—after traveling 400 kilometers to the Turkish border and then being ferried out by an airplane furnished by the Italian foreign ministry.

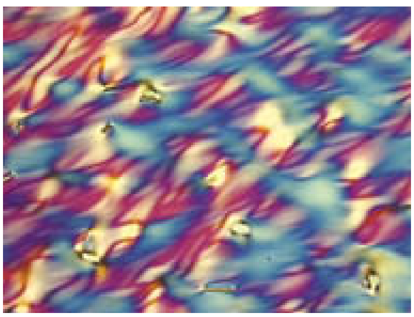
A veteran of virtually every turn-of-the-new-century conflict, Strada has begun to harbor a dream of creating a curriculum specifically focused on the medicine of war. Today medical students are trained in emergency surgery, but they are ill prepared to operate with the limited resources at the frontlines. There is a need to teach, for instance, the nuances of the triage process in which doctors have to choose which patients to operate on based on their chances of survival. "In war, you can't spend three hours operating on someone with little hope of survival, while at the same time other people with more of a chance of making it are dying," Strada says. He believes that before embarking on a relief effort, western medical workers should have training in a broad range of skills, including how to manage the physical construction of a new clinic. "We should teach war surgery but also logistics, communications and informatics, the capacity to work long hours under stress, teamwork, discipline and security issues," but most important, he notes, is an intensive course in common sense. SA

Marco Cattaneo is deputy editor at Le Scienze, *the Italian edition of* Scientific American. *Sergio Pistoi is a freelance science writer based in Arezzo, Italy.*

Seeing the Invisible

Liquid crystals may be enlisted to create pocket bioweapons detectors By DIANE MARTINDALE

Every time someone is tested for anthrax using nasal swabs or blood samples, the culturing, or growing, of the microbes from those tests can require up to two days—a painfully long wait for a nation gripped by fear of bioterrorism. With the emerging threat of biological and chemical assaults, a pressing need exists for reliable and rapid tests to detect such agents. Along with five colleagues, Christopher J. Woolverton, a biologist at Kent State University, received in January 2001 a patent (U.S.: 6,171,802) for a real-time pathogen-detection system to identify microbes, such as anthrax, in less than five minutes.



LIQUID CRYSTALS can screen for microbes.

CHRISTOPHER J. WOOLVERTON *Kent State University*

MicroDiagnosis in Bellevue, Wash., has licensed Woolverton's technology to create StatDetect, a prototype sensor the size of a credit card. The sample to be tested—say, a nasal swab—is swiped onto a thin strip, which is inserted into an opening at one end of the sensor. As the strip slides in, the sample is subdivided into several smaller samples that drop into tiny wells, or reaction chambers, containing liquid crystals (the same ones in computer displays). Embedded in the liquid crystals in each well is a different antibody so that one card is used to screen for multiple pathogens in a single test.

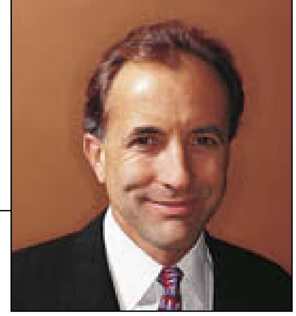
If an antibody recognizes a microbe, it will bind to it and form a complex that changes the orientation of the delicate liquid crystals, explains Ron Bromfield, president of MicroDiagnosis. When polarized light shines through the sensor card, more light will pass through the spot where the crystals have altered their position, indicating a positive reaction. "It's an all-or-nothing reaction—it reads positive or nothing," says Bromfield, who last October offered the technology to the U.S. Centers for Disease Control and Prevention to help officials with anthrax infection screening. One StatDetect card can test for up to four different agents, and it may eventually examine up to 10 in one go, including bacteria, viruses and toxins. The sensor card can also be deployed for sentinel monitoring to detect contaminants in air and water.

Whereas MicroDiagnosis's technology can spot pathogens in air and water, one patent from MolecuCare in New Milford, Conn., provides a way to stop the bugs before they can be detected. Arthur L. Matschke received a patent (U.S.: 6,228,327) for his development of an ultraviolet light–reflective chamber that can be installed within the existing air-duct and water-pipe systems of buildings and airplanes to disinfect the flow of air and water.

UV light is very effective at killing microbes if the levels of radiation are high and the exposure time is long enough. Most current methods, however, place UV lights on one end of a duct and miss striking a large percentage of contaminants: many microbes succeed in getting past the light source.

Matschke's invention, which looks like a standard duct, solves this problem. Because the inner walls are made of spun aluminum and have an ellipsoid shape—a perfect reflective surface—almost all the UV light is reflected back into the chamber instead of being absorbed, as is the case with other metals. The metal distributes constant, high levels of UV radiation evenly throughout the length of the chamber. The technology can eliminate 99.9 percent of pathogens, including hard-to-kill bacterial spores, even when the air is moving at 50,000 cubic feet per minute, Matschke says. "This is a microbe furnace—it's the fiercest method to clean air." If fears of bioterrorism persist, pathogen cooking may become a routine practice. SA

Diane Martindale is a science writer who is based in New York City.



Shermer's Last Law

Any sufficiently advanced extraterrestrial intelligence is indistinguishable from God By MICHAEL SHERMER

As scientist extraordinaire and author of an empire of science-fiction books, Arthur C. Clarke is one of the farthest-seeing visionaries of our time. His pithy quotations tug harder than those of most futurists on our collective psyches for their insights into humanity and our unique place in the cosmos. And none do so more than his famous Third Law: "Any sufficiently advanced technology is indistinguishable from magic."

This observation stimulated me to think about the impact the discovery of an extraterrestrial intelligence (ETI) would have on science and religion. To that end, I would like to immodestly propose Shermer's Last Law (I don't believe in naming laws after oneself, so as the good book says, the last shall be first and the first shall be last): "Any sufficiently advanced ETI is indistinguishable from God."

God is typically described by Western religions as omniscient and omnipotent. Because we are far from possessing these traits, how can we possibly distinguish a God who has them absolutely from an ETI who merely has them copiously relative to us? We can't. But if God were only relatively more knowing and powerful than we are, then by definition the deity *would* be an ETI!

Consider that biological evolution operates at a snail's pace compared with technological evolution (the former is Darwinian and requires generations of differential reproductive success; the latter is Lamarckian and can be accomplished within a single generation). Then, too, the cosmos is very big and very empty. Voyager 1, our most distant spacecraft, hurtling along at more than 38,000 miles per hour, will not reach the distance of even our sun's nearest neighbor, the Alpha Centauri system (which it is not headed toward), for more than 75,000 years.

Ergo, the probability that an ETI only slightly more advanced than we are will make contact is virtually nil. If we ever do find an ETI, it will be as though a million-year-old *Homo erectus* were dropped into the 21st century, given a computer and cell phone and instructed to communicate with us. The ETI would be to us as we would be to this early hominid—godlike.

Because of science and technology, our world has changed more in the past century than in the previous 100 centuries. It took 10,000 years to get from the dawn of civilization to the airplane but just 66 years to get from powered flight to a lunar landing.

Moore's Law of computer power doubling every 18 months or so is now approaching a year. Ray Kurzweil, in his book *The Age of Spiritual Machines,* calculates that there have been 32 doublings since World War II and that the singularity point—the point at which total computational power will rise to levels so far beyond anything that we can imagine that it will appear nearly infinite and thus be indistinguishable from omniscience—may be upon us as early as 2050.

Because of science, our world has changed more in the past century than in the previous 100 centuries.

When that happens, the decade that follows will put the 100,000 years before it to shame. Extrapolate out about a million years (just a blink on an evolutionary timescale and therefore a realistic estimate of how far advanced ETIs will be), and we get a gut-wrenching, mind-warping feel for how godlike these creatures would seem. In Clarke's 1953 novel, called *Childhood's End,* humanity reaches something like a singularity and must then make the transition to a higher state of consciousness. One character early in the story opines that "science can destroy religion by ignoring it as well as by disproving its tenets. No one ever demonstrated, so far as I am aware, the nonexistence of Zeus or Thor, but they have few followers now."

Although science has not even remotely destroyed religion, Shermer's Last Law predicts that the relation between the two will be profoundly affected by contact with an ETI. To find out how, we must follow Clarke's Second Law: "The only way of discovering the limits of the possible is to venture a little way past them into the impossible." *Ad astra!* SA

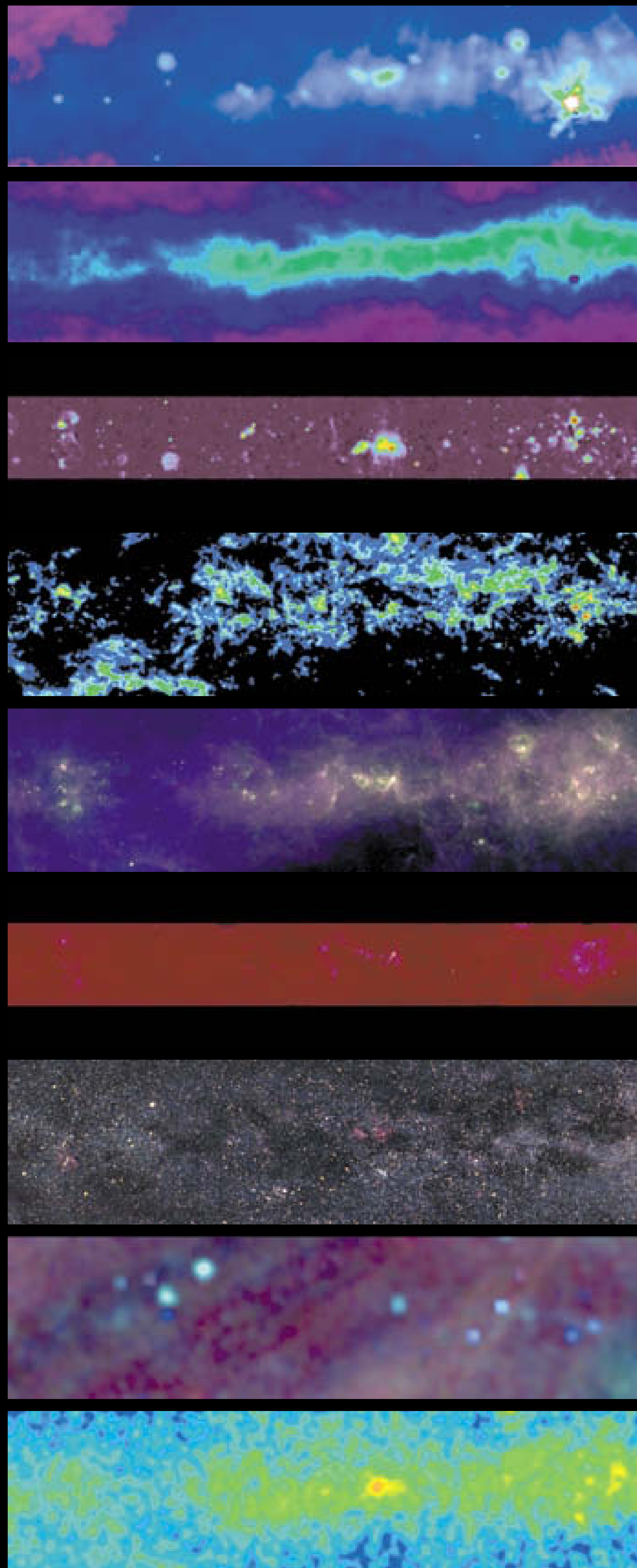
Michael Shermer is founding publisher of Skeptic *magazine (www.skeptic.com) and author of* How We Believe *and* The Borderlands of Science.

BRAD HINES

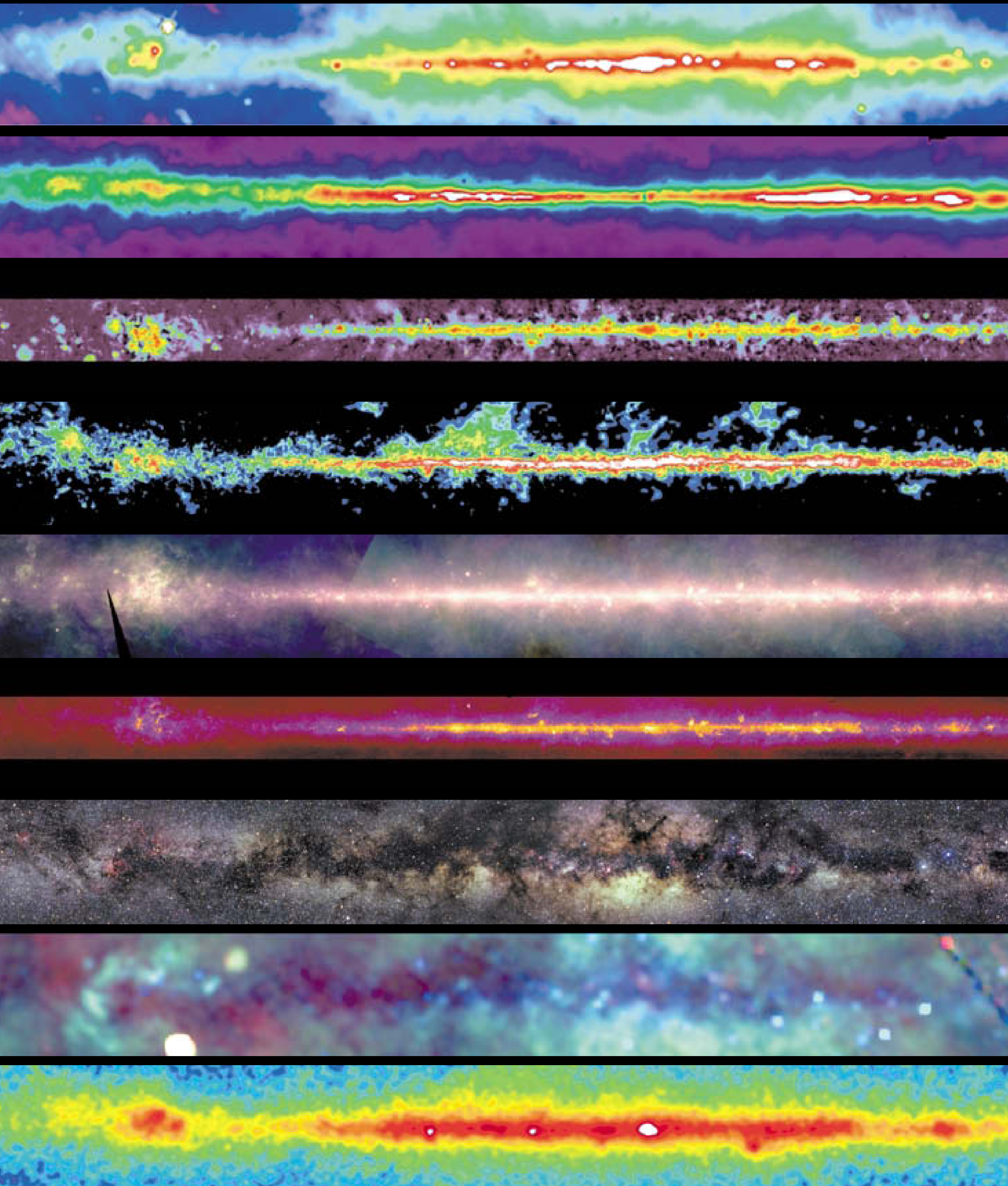
The Gas between the Stars

by Ronald J. Reynolds

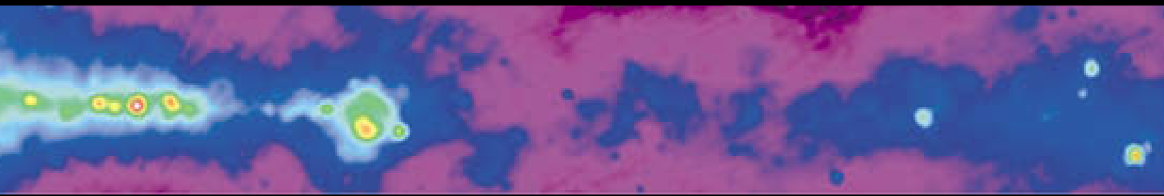
Filled with colossal fountains of hot gas and vast bubbles blown by exploding stars, the interstellar medium is far more interesting than scientists once thought



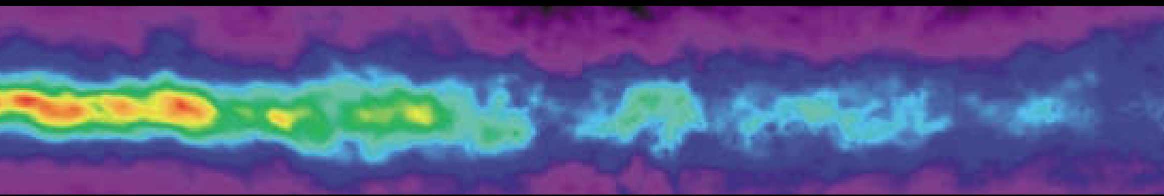
MILKY WAY GALAXY looks profoundly different depending on the frequency at which astronomers observe it. Fifty years ago, when astronomers were restricted to visible light, interstellar gas seemed like just a nuisance—blocking the real objects of interest, the stars. Today scientists think the gas may be as important to the evolution of the galaxy as are the stars. These panels appear on a poster prepared by the NASA Goddard Space Flight Center; for more information, visit http://nvo.gsfc.nasa.gov/mw/mmw_sci.html



NASA GSFC ASTROPHYSICS DATA FACILITY (*radio continuum [408 MHz], atomic hydrogen, far-infrared, x-ray and gamma ray*); ROY DUNCAN *Software Infrastructure Group* (*radio continuum (2.4–2.7 GHz)*); THOMAS DAME *Harvard-Smithsonian Center for Astrophysics* (*molecular hydrogen*); STEPHAN D. PRICE *Hanscom AFB* (*mid-infrared*); AXEL MELLINGER *University of Potsdam* (*visible light*)



RADIO CONTINUUM
(408 MHz)
Reveals fast-moving electrons, found especially at sites of past supernovae

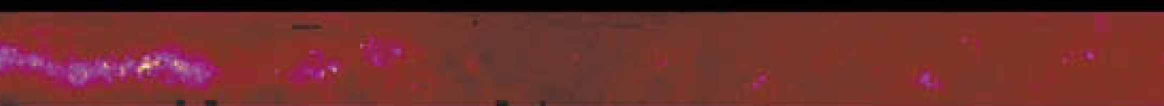


ATOMIC HYDROGEN
(1420 MHz)
Reveals neutral atomic hydrogen in interstellar clouds and diffuse gas

RADIO CONTINUUM
(2.4–2.7 GHz)
Reveals warm, ionized gas and high-energy electrons

MOLECULAR HYDROGEN
(115 GHz)
Reveals molecular hydrogen (as traced by carbon monoxide) in cold clouds

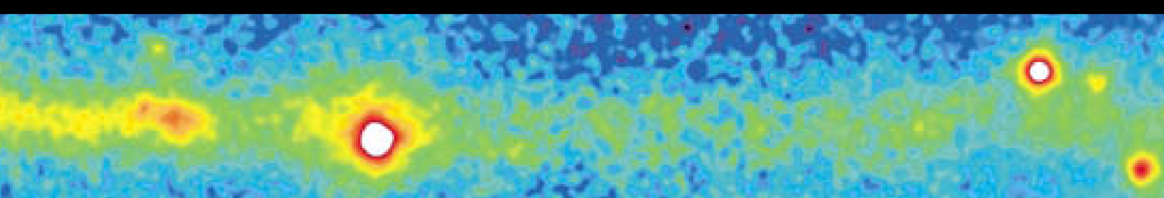
FAR-INFRARED
(12–100 microns)
Reveals dust warmed by starlight, specially in star-forming regions



MID-INFRARED
(6.8–10.8 microns)
Reveals complex molecules in interstellar clouds, as well as reddish stars

VISIBLE LIGHT
(0.4–0.6 micron)
Reveals nearby stars and tenuous ionized gas; dark areas are cold and dense

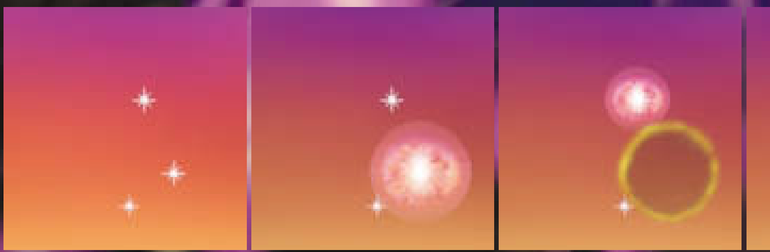
X-RAY
(0.25–1.5 kiloelectron-volt)
Reveals hot, shocked gas from supernovae



GAMMA RAY
(greater than 300 megaelectron-volts)
Reveals high-energy phenomena such as pulsars and cosmic-ray collisions

The Galaxy's Dynamic Atmosphere

The views above and on the preceding page are cross sections through the Milky Way.



1 A superbubble originates with a cluster of massive stars.

2 One star goes supernova, forming a bubble of hot, low-density gas.

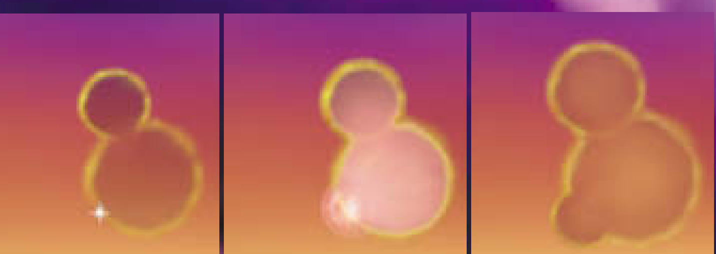
3 Because massive stars have similar lifespans, another one soon blows.

4 wi
bu

The term “interstellar medium” once conjured up a picture like the one at right: frigid, inky clouds of gas and dust in repose near the galactic plane. Today astronomers recognize the medium as a protean atmosphere roiled by supernova explosions. Gas gushes through towering chimneys, then showers back down in mighty fountains.

C. HOWK AND BLAIR SAVAGE *University of Wisconsin* AND N. SHARP *NOAO*

Galaxy NGC 891 in visible light



4 The two bubbles link up. Stellar ...nds help energize the ...bbles.

5 A third explodes. The interstellar medium starts to look like Swiss cheese.

6 All three bubbles link up, forming a passage for hot gas and radiation.

Composition of the Galactic Atmosphere

	IN CLOUDS		BETWEEN CLOUDS		
Component	H_2	H I	WARM H I	WARM H II	HOT H II
Temperature (K)	15	120	8,000	8,000	$\sim 10^6$
Midplane Density (cm^{-3})	200	25	0.3	0.15	0.002
Thickness of Layer (parsecs)	150	200	1,000	2,000	6,000
Volume Fraction (%)	0.1	2	35	20	43
Mass Fraction (%)	18	30	30	20	2

Some of the interstellar medium takes the form of discrete clouds of atomic hydrogen (H I) or molecular hydrogen (H_2); most of the rest is in a pervasive ionized (H II) or atomic gas. Intermixed is a trace amount of other elements. The total mass is about one fifth of the galaxy’s stars.

We often think of the moon as a place, but in fact it is a hundred million places, an archipelago of solitude. You could go from 100 degrees below zero to 100 degrees above with a small step. You could yell in your friend's ear and he would never hear you. Without an atmosphere to transmit heat or sound, each patch of the moon is an island in an unnavigable sea.

The atmosphere of a planet is what binds its surface into a unified whole. It lets conditions such as temperature vary smoothly. More dramatically, events such as the impact of an asteroid, the eruption of a volcano and the emission of gas from a factory's chimney can have effects that reach far beyond the spots where they took place. Local phenomena can have global consequences. This characteristic of atmospheres has begun to capture the interest of astronomers who study the Milky Way galaxy.

For many years, we have known that an extremely thin atmosphere called the interstellar medium envelops our galaxy and threads the space between its billions of stars. Until fairly recently, the medium seemed a cold, static reservoir of gas quietly waiting to condense into stars. You barely even notice it when looking up into the starry sky. Now we recognize the medium as a tempestuous mixture with an extreme diversity of density, temperature and ionization. Supernova explosions blow giant bubbles; fountains and chimneys may arch above the spiral disk; and clouds could be falling in from beyond the disk. These and other processes interconnect far-flung reaches of our galaxy much as atmospheric phenomena convey disturbances from one side of Earth to the other.

In fact, telescopes on the ground and in space are showing the galaxy's atmosphere to be as complex as any planet's. Held by the combined gravitational pull of the stars and other matter, permeated by starlight, energetic particles and a magnetic field, the interstellar medium is continuously stirred, heated, recycled and transformed. Like any atmosphere, it has its highest density and pressure at the "bottom," in this case the plane that defines the middle of the galaxy, where the pressure must balance the weight of the medium from "above." Dense concentrations of gas—clouds—form near the midplane, and from the densest subcondensations, stars precipitate.

When stars exhaust their nuclear fuel and die, those that are at least as massive as the sun expel much of their matter back into the interstellar medium. Thus, as the galaxy ages, each generation of stars pollutes the medium with heavy elements. As in the water cycle on Earth, precipitation is followed by "evaporation," so that material can be recycled over and over again.

Up in the Air

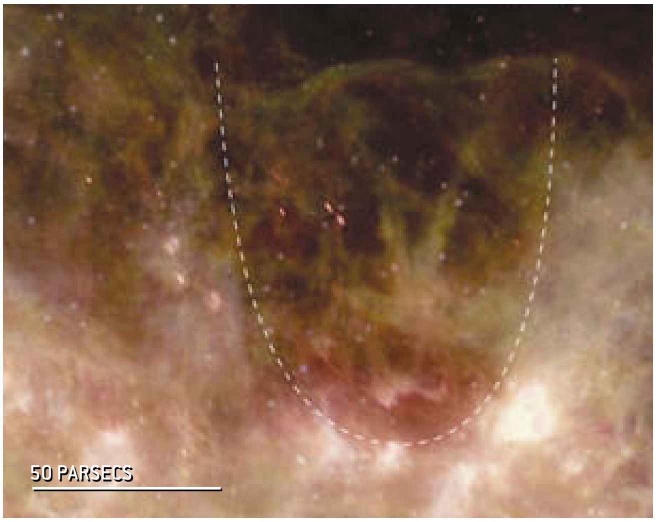
THINKING OF THE INTERSTELLAR medium as a true atmosphere brings unity to some of the most pressing problems in astrophysics. First and foremost is star formation. Although astronomers have known the basic principles for decades, they still do not grasp exactly what determines when and at what rate stars precipitate from the interstellar medium. Theorists used to explain the creation of stars only in terms of the local conditions within an isolated gas cloud. Now they are considering conditions in the galaxy as a whole.

Not only do these conditions influence star formation, they are influenced by it. What one generation of stars does determines the environment in which subsequent generations are born, live and die. Understanding this feedback—the sway of stars, especially the hottest, rarest, most massive stars, over the large-scale properties of the interstellar medium—is another of the great challenges for researchers. Feedback can be both positive and negative. On the one hand, massive stars can heat and ionize the medium and cause it to bulge out from the midplane. This expansion increases the ambient pressure, compressing the clouds and perhaps triggering their collapse into a new generation of stars. On the other hand, the heating and ionization can also agitate clouds, inhibiting the birth of new stars. When the largest stars blow up, they can even destroy the clouds that gave them birth. In fact, negative feedback could explain why the gravitational collapse of clouds into stars is so inefficient. Typically only a few percent of a cloud's mass becomes stars.

A third conundrum is that star formation often occurs in sporadic but intense bursts. In the Milky Way the competing feedback effects almost balance out, so that stars form at an unhurried pace—just 10 per year on average. In some galaxies, however, such as the "exploding galaxy" M82, positive feedback has gained the upper hand. Starting 20 million to 50 million years ago, star formation in the central parts of M82 began running out of control, proceeding 10 times faster than before. Our galaxy, too, may have had sporadic bursts. How these starbursts occur and what turns them off must be tied to the complex relation between stars and the tenuous atmosphere from which they precipitate.

Finally, astronomers debate how quickly the atmospheric activity is petering out. The majority of stars—those less massive than the sun, which live tens or even hundreds of billions of years—do not contribute to the feedback loops. More and more of the interstellar gas is being locked up into very long lived stars. Eventually all the spare gas in our Milky Way may be exhausted, leaving only stellar dregs behind. How soon this will happen depends on whether the Milky Way is a closed box. Recent observations suggest that the galaxy is still an open system, both gaining and losing mass to its cosmic surroundings. High-velocity clouds of relatively unpolluted hydrogen appear to be raining down from intergalactic space, rejuvenating our galaxy. Meanwhile the galaxy may be shedding gas in the form of a high-speed wind from its outer atmosphere, much as the sun slowly sheds mass in the solar wind.

DON DIXON



CONE-SHAPED SUPERBUBBLE, known as the W4 Chimney (*dotted line*), was probably created by a cluster of massive stars. In the center is a filament of gas with a V shape, as if swept back by the force of supernova explosions and stellar outflows. This image is a false-color composite of radio and infrared maps of cool hydrogen gas.

JAYANNE ENGLISH *University of Manitoba*; CANADIAN GALACTIC PLANE SURVEY AND RUSS TAYLOR *University of Calgary*

Hot and Cold Running Hydrogen

TO TACKLE THESE PROBLEMS, those of us who study the interstellar medium have first had to identify its diverse components. Astronomers carried out the initial step, an analysis of its elemental composition, in the 1950s and 1960s using the spectra of light emitted by bright nebulae, such as the Orion Nebula. In terms of the number of atomic nuclei, hydrogen constitutes 90 percent, helium about 10 percent, and everything else—from lithium to uranium—just a trace, about 0.1 percent.

Because hydrogen is so dominant, the structure of the galaxy's atmosphere depends mainly on what forms the hydrogen takes. Early observations were sensitive primarily to cooler, neutral components. The primary marker of interstellar material is the most famous spectral line of astronomy: the 1,420-megahertz (21-centimeter) line emitted by neutral hydrogen atoms, denoted by astronomers as H I. Beginning in the 1950s, radio astronomers mapped out the distribution of H I within the galaxy. It resides in lumps and filaments with densities of 10 to 100 atoms per cubic centimeter and temperatures near 100 kelvins, embedded in a more diffuse, thinner (roughly 0.1 atom per cubic centimeter) and warmer (a few thousand kelvins) phase. Most of the H I is close to the galactic midplane, forming a gaseous disk about 300 parsecs (1,000 light-years) thick, roughly half the thickness of the main stellar disk you see when you notice the Milky Way in the night sky.

Hydrogen can also come in a molecular form (H_2), which is extremely difficult to detect directly. Much of the information about it has been inferred from high-frequency radio observations of the trace molecule carbon monoxide. Where carbon monoxide exists, so should molecular hydrogen. The molecules appear to be confined to the densest and coldest clouds—the places where starlight, which breaks molecules into their constituent atoms, cannot penetrate. These dense clouds, which are active sites of star formation, are found in a thin layer (100 parsecs thick) at the very bottom of the galactic atmosphere.

Until very recently, hydrogen molecules were seen directly only in places where they were being destroyed—that is, converted to atomic hydrogen—by a nearby star's ultraviolet radiation or wind of outflowing particles. In these environments, H_2 glows at an infrared wavelength of about 2.2 microns. In the past few years, however, orbiting spectrographs, such as the shuttle-based platform called ORFEUS-SPAS and the new Far Ultraviolet Spectroscopic Explorer (FUSE) satellite, have sought molecular hydrogen at ultraviolet wavelengths near 0.1 micron. These instruments look for hydrogen that is backlit by distant stars and quasars: the H_2 leaves telltale absorption lines in the ultraviolet spectra of those objects. The advantage of this approach is that it can detect molecular hydrogen in quiescent regions of the galaxy, far from any star.

To general astonishment, two teams, led respectively by Philipp Richter of the University of Wisconsin and Wolfgang Gringel of the University of Tübingen in Germany, have discovered H_2 not just in the usual places—the high-density clouds located within the galactic disk—but also in low-density areas far outside the disk. This is a bit of a mystery, because high densities are needed to shield the molecules from the ravages of starlight. Perhaps a population of cool clouds extends much farther from the midplane than previously believed.

A third form of hydrogen is a plasma of hydrogen ions. Astronomers used to assume that ionized hydrogen was confined to a few small, isolated locations—the glowing nebulae near luminous stars and the wispy remnants left over from supernovae. Advances in detection technology and the advent of space astronomy have changed that. Two new components of our galaxy's atmosphere have come into view: hot (10^6 kelvins) and warm (10^4 kelvins) ionized hydrogen (H II).

Like the recently detected hydrogen molecules, these H II phases stretch far above the cold H I cloud layer, forming a thick gaseous "halo" around the entire galaxy. "Interstellar" no longer seems an appropriate description for these outermost parts of our galaxy's atmosphere. The hotter phase may extend thousands of parsecs from the midplane and thin out to a density near 10^{-3} ion per cubic centimeter. It is our galaxy's corona, analogous to the extended hot atmosphere of our sun. As in the case of the solar corona, the mere existence of the galactic corona implies an unconventional source of energy to maintain the high temperatures. Supernova shocks and fast stellar winds appear to do

THE AUTHOR

RONALD J. REYNOLDS bought a 4.25-inch reflecting telescope in sixth grade and used it to take pictures of the moon. But it wasn't until he started his Ph.D. in physics that he took his first astronomy course and began to consider a career in the subject. Today Reynolds is an astronomy professor at the University of Wisconsin–Madison. He has designed and built high-sensitivity spectrometers to study warm ionized gas in the Milky Way galaxy. He is principal investigator for the Wisconsin H-Alpha Mapper, which spent two years mapping hydrogen over the entire northern sky.

the trick. Coexisting with the hot plasma is the warm plasma, which is powered by extreme ultraviolet radiation. The weight of these extended layers increases the gas pressure at the midplane, with significant effects on star formation. Other galaxies appear to have coronas as well. The Chandra X-ray Observatory has recently seen one around the galaxy NGC 4631 [*see middle illustration on next page*].

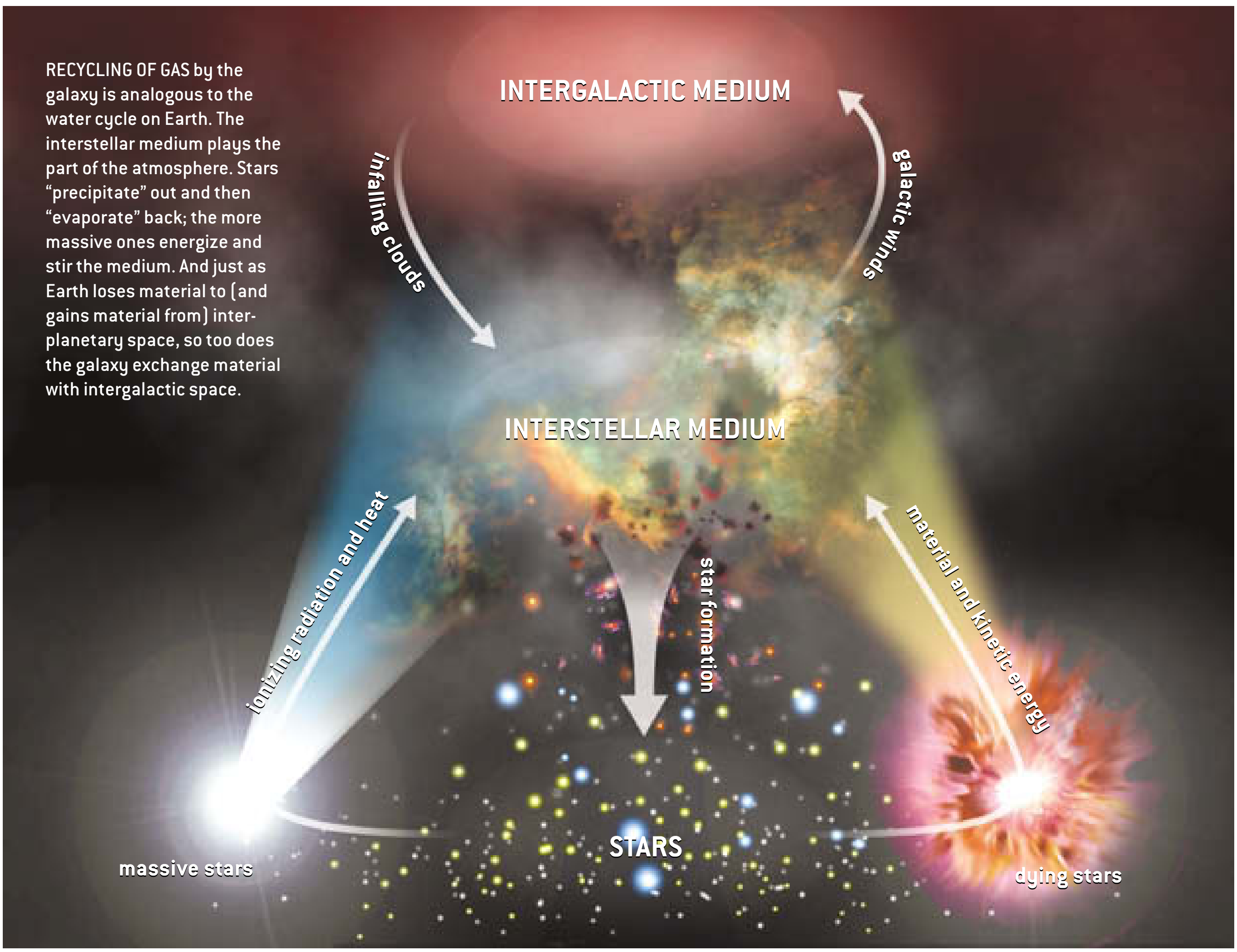
Blowing Bubbles

HAVING IDENTIFIED these new, more energetic phases of the medium, astronomers have turned to the question of how the diverse components behave and interrelate. Not only does the interstellar medium cycle through stars, it changes from H_2 to H I to H II and from cold to hot and back again. Massive stars are the only known source of energy powerful enough to account for all this activity. A study by Ralf-Jürgen Dettmar of the University of Bochum in Germany found that galaxies with a larger-than-average massive star population seem to have atmospheres that are more extended or puffed up. How the stars wield power over an entire galaxy is somewhat unclear, but astronomers generally pin the blame on the creation of hot ionized gas.

This gas appears to be produced by the high-velocity (100 to 200 kilometers per second) shock waves that expand into the interstellar medium following a supernova. Depending on the density of the gas and strength of the magnetic field in the ambient medium, the spherically expanding shock may clear out a cavity 50 to 100 parsecs in radius—a giant bubble.

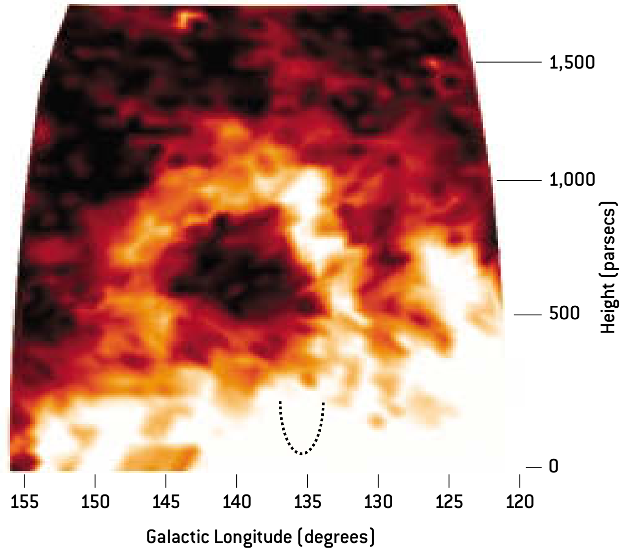
In doing so, the shock accelerates a small fraction of the ions and electrons to near light speed. Known as cosmic rays, these fleet-footed particles are one way that stellar death feeds back (both positively and negatively) into stellar birth. Cosmic rays raise the pressure of the interstellar medium; higher pressures, in turn, compress the dense molecular clouds and increase the chance that they will collapse into stars. By ionizing some of the hydrogen, the cosmic rays also drive chemical reactions that synthesize complex molecules, some of which are the building blocks of life as we know it. And because the ions attach themselves to magnetic field lines, they trap the field within the clouds, which slows the rate of cloud collapse into stars.

If hot bubbles are created frequently enough, they could interconnect in a vast froth. This idea was first advanced in the 1970s by Barham Smith and Donald Cox of the University of Wisconsin–Madison. A couple of years later Christopher F. McKee of the University of California at Berkeley and Jeremiah P.

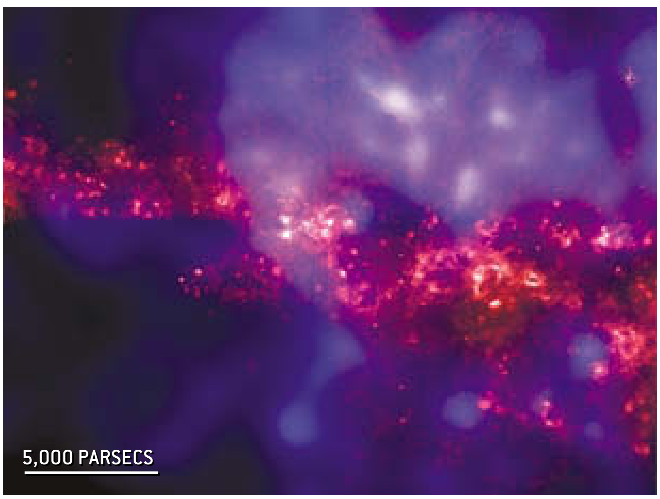


RECYCLING OF GAS by the galaxy is analogous to the water cycle on Earth. The interstellar medium plays the part of the atmosphere. Stars "precipitate" out and then "evaporate" back; the more massive ones energize and stir the medium. And just as Earth loses material to (and gains material from) interplanetary space, so too does the galaxy exchange material with intergalactic space.

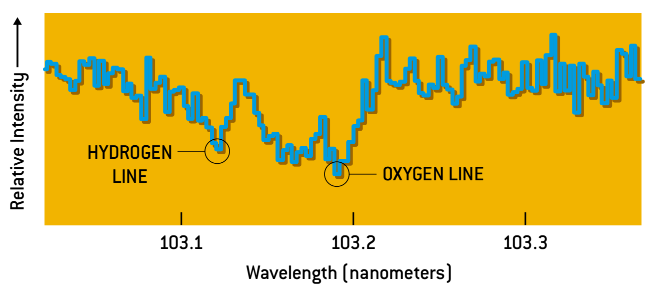
DON DIXON



ARCHING OVER THE DISK of our galaxy is an enormous loop of warm ionized hydrogen. It is located just above the W4 Chimney (*dotted line*), shown on page 40. The same star cluster may account for both of these structures.



ENVELOPING THE DISK of the galaxy NGC 4631 is a hot plasma (*blue and purple*), seen by the Chandra X-ray Observatory. The Ultraviolet Imaging Telescope revealed massive stars within the disk (*orange*).



HOT PLASMA surrounds our galaxy, too. The Far Ultraviolet Spectroscopic Explorer detected this spectral line of strongly ionized oxygen in a gas cloud backlit by a quasar. The cloud is at least five kiloparsecs from the disk.

Ostriker of Princeton University argued that the hot phase should occupy 55 to 75 percent of interstellar space. Cooler neutral phases would be confined to isolated clouds within this ionized matrix—essentially the inverse of the traditional picture, in which the neutral gas dominates and the ionized gas is confined to small pockets.

Recent observations seem to support this upending of conventional wisdom. The nearby spiral galaxy M101, for example, has a circular disk of atomic hydrogen gas riddled with holes—presumably blown by massive stars. The interstellar medium of another galaxy, seven billion light-years distant, also looks like Swiss cheese. But the amount of hot gas and its influence on the structure of galactic atmospheres still occasion much debate.

Chimneys and Fountains

THE SUN ITSELF APPEARS to be located within a hot bubble, which has revealed itself in x-rays emitted by highly ionized trace ions such as oxygen. Called the Local Bubble, this region of hot gas was apparently created by a nearby supernova about one million years ago.

An even more spectacular example lies 450 parsecs from the sun in the direction of the constellations Orion and Eridanus. It was the subject of a recent study by Carl Heiles of the University of California at Berkeley and his colleagues. The Orion-Eridanus Bubble was formed by a star cluster in the constellation Orion. The cluster is of an elite type called an OB association—a bundle of the hottest and most massive stars, the O- and B-type stars, which are 20 to 60 times heavier than the sun (a G-type star) and 10^3 to 10^5 times brighter. The spectacular deaths of these short-lived stars in supernovae over the past 10 million years have swept the ambient gas into a shell-like skin around the outer boundary of the bubble. In visible light the shell appears as a faint lacework of ionized loops and filaments. The million-degree gas that fills its interior gives off a diffuse glow of x-rays.

The entire area is a veritable thunderstorm of star formation, with no sign of letting up. Stars continue to precipitate from the giant molecular cloud out of which the OB association emerged. One of the newest O stars, theta[1] C Orionis, is ionizing a small piece of the cloud—producing the Orion Nebula. In time, however, supernovae and ionizing radiation will completely disrupt the molecular cloud and dissociate its molecules. The molecular hydrogen will turn back into atomic and ionized hydrogen, and star formation will cease. Because the violent conversion process will increase the pressure in the interstellar medium, the demise of this molecular cloud may mean the birth of stars elsewhere in the galaxy.

Galactic bubbles should buoyantly lift off from the galactic midplane, like a thermal rising above the heated ground on Earth. Numerical calculations, such as those recently made by Mordecai-Mark MacLow of the American Museum of Natural History in New York City and his colleagues, suggest that bubbles can ascend all the way up into the halo of the galaxy. The result is a cosmic chimney through which hot gas spewed by supernovae near the midplane can vent to the galaxy's upper atmosphere. There the gas will cool and rain back onto the

RONALD J. REYNOLDS (*top*); NASA AND DANIEL WANG *University of Massachusetts at Amherst* (*x-ray imaging*) AND NASA/UIT (*ultraviolet imaging*) (*middle*); KENNETH R. SEMBACH *Johns Hopkins University* AND THE FUSE SCIENCE TEAM (*bottom*) galactic disk. In this case, the superbubble and chimney become a galactic-scale fountain.

Such fountains could perhaps be the source of the hot galactic corona and even the galaxy's magnetic field. According to calculations by Katia M. Ferrière of the Midi-Pyrénées Observatory in France, the combination of the updraft and the rotation of the galactic disk would act as a dynamo, much as motions deep inside the sun and Earth generate magnetic fields.

To be sure, observers have yet to prove the pervasive nature of the hot phase or the presence of fountains. The Orion-Eridanus bubble extends 400 parsecs from the midplane, and a similar superbubble in Cassiopeia rises 230 parsecs, but both have another 1,000 to 2,000 parsecs to go to reach the galactic corona. Magnetic fields and cooler, denser ionized gas could make it difficult or impossible for superbubbles to break out into the halo. But then, where did the hot corona come from? No plausible alternative is known.

Getting Warm

THE WARM (10^4 KELVINS) plasma is as mysterious as its hot relative. Indeed, in the traditional picture of the interstellar medium, the widespread presence of warm ionized gas is simply impossible. Such gas should be limited to very small regions of space—the emission nebulae, such as the Orion Nebula, that immediately surround ultramassive stars. These stars account for only one star in five million, and most of the interstellar gas (the atomic and molecular hydrogen) is opaque to their photons. So the bulk of the galaxy should be unaffected.

Yet warm ionized gas is spread throughout interstellar space. One recent survey, known as WHAM, finds it even in the galactic halo, very far from the nearest O stars. Ionized gas is similarly widespread in other galaxies. This is a huge mystery. How did the ionizing photons manage to stray so far from their stars?

Bubbles may be the answer. If supernovae have hollowed out significant parts of the interstellar medium, ionizing photons may be able to travel large distances before being absorbed by neutral hydrogen. The Orion OB association provides an excellent example of how this could work. The O stars sit in an immense cavity carved out by earlier supernovae. Their photons now travel freely across the cavity, striking the distant bubble wall and making it glow. If galactic fountains or chimneys do indeed stretch up into the galactic halo, they could explain not only the hot corona but also the pervasiveness of warm ionized gas.

A new WHAM image of the Cassiopeia superbubble reveals a possible clue: a loop of warm gas arching far above the bubble, some 1,200 parsecs from the midplane. The outline of this loop bears a loose resemblance to a chimney, except that it has not (yet) broken out into the Milky Way's outer halo. The amount of energy required to produce this gigantic structure is enormous—more than that available from the stars in the cluster that formed the bubble. Moreover, the time required to create it is 10 times the age of the cluster. So the loop may be a multigenerational project, created by a series of distinct bursts of star formation predating the cluster we see today. Each burst reenergized and expanded the bubble created by the preceding burst.

Round and Round

THAT LARGE REGIONS of the galaxy can be influenced by the formation of massive stars in a few localized regions seems to require that star formation somehow be coordinated over long periods of time. It may all begin with a single O-type star or a cluster of such stars in a giant molecular cloud. The stellar radiation, winds and explosions carve a modest cavity out of the surrounding interstellar medium. In the process the parent cloud is probably destroyed. Perchance this disturbance triggers star formation in a nearby cloud, and so on, until the interstellar medium in this corner of the galaxy begins to resemble Swiss cheese. The bubbles then begin to overlap, coalescing into a superbubble. The energy from more and more O-type stars feeds this expanding superbubble until its natural buoyancy stretches it from the midplane up toward the halo, forming a chimney.

The superbubble is now a pathway for hot interior gas to spread into the upper reaches of the galactic atmosphere, producing a widespread corona. Now, far from its source of energy, the coronal gas slowly begins to cool and condense into clouds. These clouds fall back to the galaxy's midplane, completing the fountainlike cycle and replenishing the galactic disk with cool clouds from which star formation may begin anew.

Even though the principal components and processes of our galaxy's atmosphere seem to have been identified, the details remain uncertain. Progress will be made as astronomers continue to study how the medium is cycled through stars, through the different phases of the medium, and between the disk and the halo. Observations of other galaxies give astronomers a bird's-eye view of the interstellar goings-on.

Some crucial pieces could well be missing. For example, are stars really the main source of power for the interstellar medium? The loop above the Cassiopeia superbubble looks uncomfortably similar to the prominences that arch above the surface of the sun. Those prominences owe much to the magnetic field in the solar atmosphere. Could it be that magnetic activity dominates our galaxy's atmosphere, too? If so, the analogy between galactic atmospheres and their stellar and planetary counterparts may be even more apt than we think. SA

MORE TO EXPLORE

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Far Ultraviolet Spectroscopic Explorer Observations of O VI Absorption in the Galactic Halo. Blair D. Savage et al. in *Astrophysical Journal Letters,* Vol. 538, No. 1, pages L27–L30; July 20, 2000. Preprint available at **arXiv.org/abs/astro-ph/0005045**

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Detection of a Large Arc of Ionized Hydrogen Far Above the CAS OB6 Association: A Superbubble Blowout into the Galactic Halo? Ronald J. Reynolds, N. C. Sterling and L. Matthew Haffner in *Astrophysical Journal Letters,* Vol. 558, No. 2, pages L101–L104; September 10, 2001. Preprint available at **arXiv.org/abs/astro-ph/0108046**

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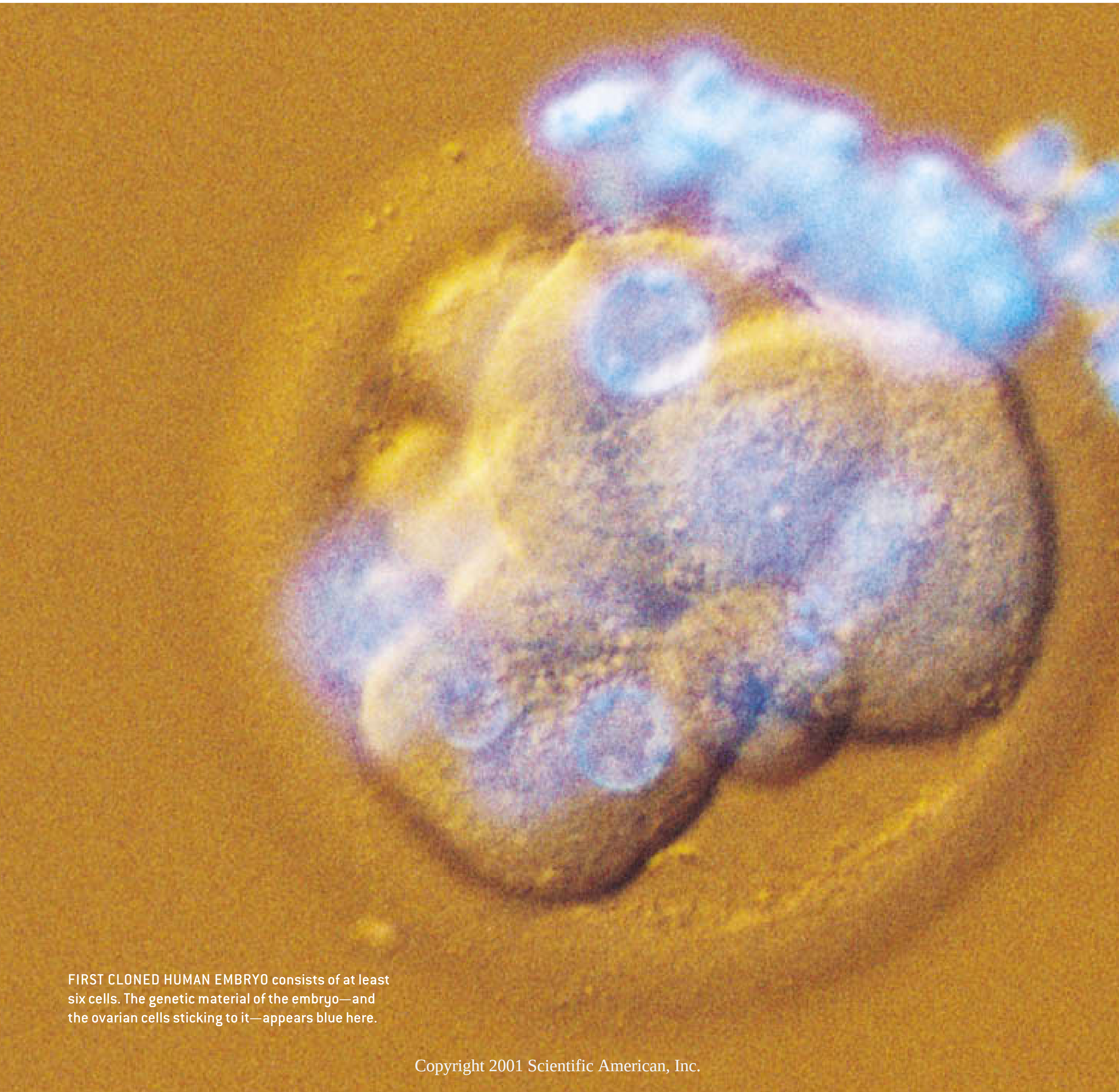
EXCLUSIVE

The First Human Cloned

By Jose B. Cibelli, Robert P. Lanza and Michael D. West, with Carol Ezzell



FIRST CLONED HUMAN EMBRYO consists of at least six cells. The genetic material of the embryo—and the ovarian cells sticking to it—appears blue here.

Embryo

JOSE B. CIBELLI

Cloned early-stage human embryos—and human embryos generated only from eggs, in a process called parthenogenesis—now put therapeutic cloning within reach

THEY WERE SUCH TINY DOTS, YET THEY HELD SUCH immense promise. After months of trying, on October 13, 2001, we came into our laboratory at Advanced Cell Technology to see under the microscope what we'd been striving for—little balls of dividing cells not even visible to the naked eye. Insignificant as they appeared, the specks were precious because they were, to our knowledge, the first human embryos produced using the technique of nuclear transplantation, otherwise known as cloning.

With a little luck, we hoped to coax the early embryos to divide into hollow spheres of 100 or so cells called blastocysts. We intended to isolate human stem cells from the blastocysts to serve as the starter stock for growing replacement nerve, muscle and other tissues that might one day be used to treat patients with a variety of diseases. Unfortunately, only one of the embryos progressed to the six-cell stage, at which point it stopped dividing. In a similar experiment, however, we succeeded in prompting human eggs—on their own, with no sperm to fertilize them—

THE AUTHORS

JOSE B. CIBELLI, ROBERT P. LANZA and *MICHAEL D. WEST* are vice president of research, vice president of medical and scientific development, and president and CEO, respectively, of Advanced Cell Technology, a privately held biotechnology company in Worcester, Mass. Cibelli received his D.V.M. from the University of La Plata in Argentina and his Ph.D. from the University of Massachusetts at Amherst. His research led to the creation of the first cloned genetically modified calves in 1998. Lanza has an M.D. from the University of Pennsylvania. He is a former Fulbright scholar and is the author or editor of numerous popular and scientific books, including the text *Principles of Tissue Engineering*. West holds a Ph.D. from Baylor College of Medicine and is particularly interested in aging and stem cells. From 1990 until 1998 he was founder, director and vice president of Geron Corporation in Menlo Park, Calif., where he initiated and managed research programs in the biology of telomeres (the ends of chromosomes, which shrink during aging) and the effort to derive human embryonic stem cells. Carol Ezzell is a staff writer and editor.

to develop parthenogenetically into blastocysts. We believe that together these achievements, the details of which we reported November 25 in the online journal *e-biomed: The Journal of Regenerative Medicine,* represent the dawn of a new age in medicine by demonstrating that the goal of therapeutic cloning is within reach.

Therapeutic cloning—which seeks, for example, to use the genetic material from patients' own cells to generate pancreatic islets to treat diabetes or nerve cells to repair damaged spinal cords—is distinct from reproductive cloning, which aims to implant a cloned embryo into a woman's uterus leading to the birth of a cloned baby. We believe that reproductive cloning has potential risks to both mother and fetus that make it unwarranted at this time, and we support a restriction on cloning for reproductive purposes until the safety and ethical issues surrounding it are resolved.

Disturbingly, the proponents of reproductive cloning are trying to co-opt the term "therapeutic cloning" by claiming that employing cloning techniques to create a child for a couple who cannot conceive through any other means treats the disorder of infertility. We object to this usage and feel that calling such a procedure "therapeutic" yields only confusion.

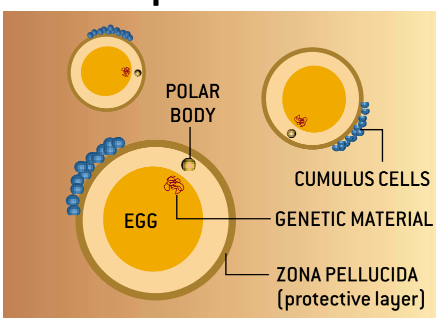
What We Did

WE LAUNCHED OUR ATTEMPT to create a cloned human embryo in early 2001. We began by consulting our ethics advisory board, a panel of independent ethicists, lawyers, fertility specialists and counselors that we had assembled in 1999 to guide the company's research efforts on an ongoing basis. Under the chairmanship of Ronald M. Green, director of the Ethics Institute at Dartmouth College, the board considered five key issues [*see box beginning on page 48*] before recommending that we go ahead.

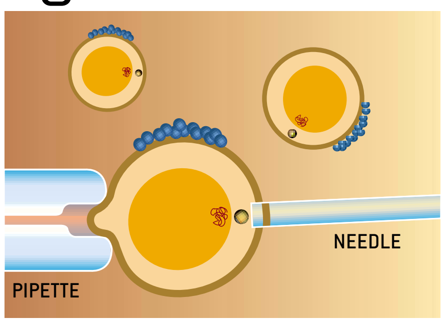
The next step was to recruit women willing to contribute eggs to be used in the cloning procedure and also collect cells from individuals to be cloned (the donors). The cloning process appears simple, but success depends on many small factors, some of which we do not yet understand. In the basic nuclear transfer technique, scientists use an extremely fine needle to suck the genetic material from a mature egg. They then inject the nucleus of the donor cell (or sometimes a whole cell) into the enucleated egg and incubate it under special conditions that prompt it to divide and grow [*see illustration on these two pages*].

We found women willing to contribute eggs on an anonymous basis for use in our research by placing advertisements in

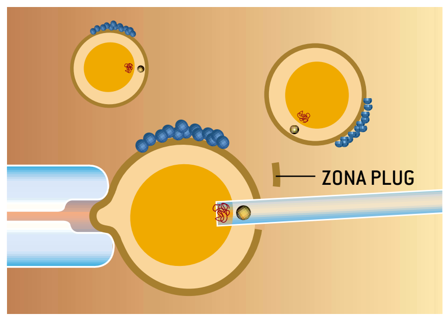
Therapeutic Cloning: How It's Done



1 Eggs are coaxed to mature in a culture dish. Each has a remnant egg cell called the polar body and cumulus cells from the ovary clinging to it.

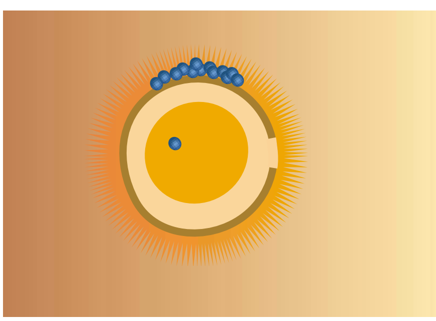


2 While an egg is held still with a pipette, a needle is used to drill through the zona pellucida, removing a plug.

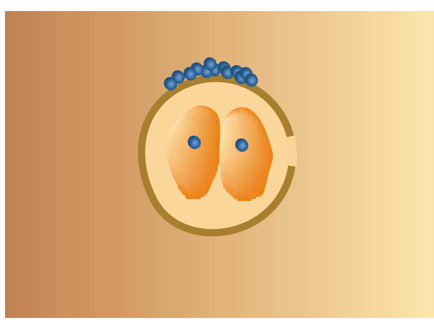


3 After ejecting the zona plug, the needle is inserted back in the egg through the hole to withdraw and discard the polar body and the egg's genetic material.

4

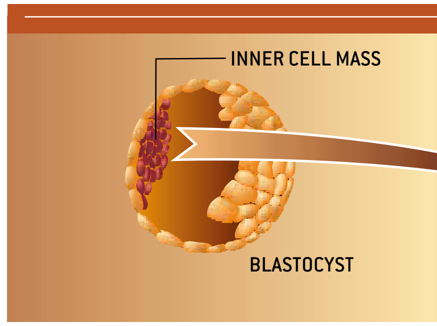


6 The injected egg is exposed to a mixture of chemicals and growth factors designed to activate it to divide.

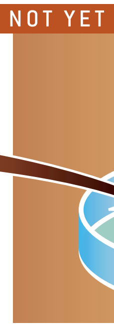


7 After roughly 24 hours, the activated egg begins dividing. The cells contain genetic material only from the injected cumulus cell.

NOT YET



8 By the fourth or fifth day, a hollow ball of roughly 100 cells has formed. It holds a clump of cells called the inner cell mass that contains stem cells.



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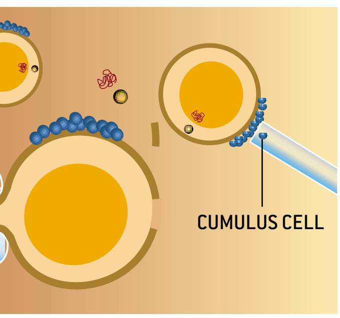
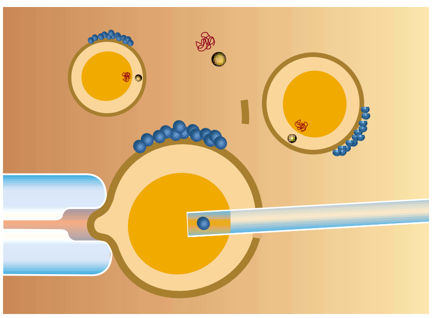
publications in the Boston area. We accepted women only between the ages of 24 and 32 who had at least one child. Interestingly, our proposal appealed to a different subset of women than those who might otherwise contribute eggs to infertile couples for use in in vitro fertilization. The women who responded to our ads were motivated to give their eggs for research, but many would not have been interested in having their eggs used to generate a child they would never see. (The donors were recruited and the eggs were collected by a team led by Ann A. Kiessling-Cooper of Duncan Holly Biomedical in Somerville, Mass. Kiessling was also part of the deliberations concerning ethical issues related to the egg contributors.)

We asked potential egg contributors to submit to psychological and physical tests, including screening for infectious diseases, to ensure that the women were healthy and that contributing eggs would not adversely affect them. We ended up with 12 women who were good candidates to contribute eggs. In the meantime, we took skin biopsies from several other anonymous individuals to isolate cells called fibroblasts for use in the cloning procedure. Our group of fibroblast donors includes people of varying ages who are generally healthy or who have a disorder such as diabetes or spinal cord injury—

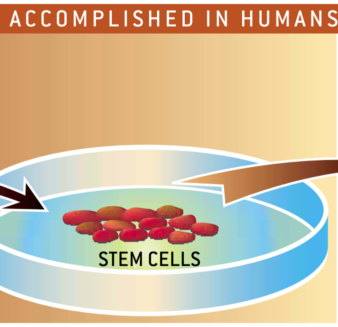


A cumulus cell from another egg is taken up into the needle. Cells called fibroblasts (or their nuclei) can also be used in this step.

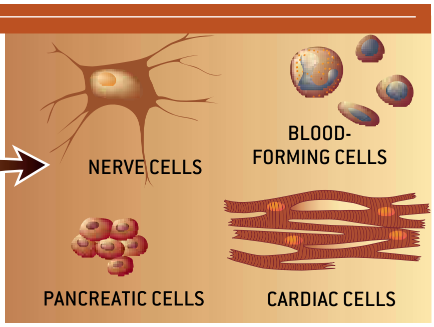


5 The cumulus cell is injected deep into the egg that has been stripped of its genetic material.

ACCOMPLISHED IN HUMANS



The blastocyst is broken open, and the inner cell mass is grown in a culture dish to yield stem cells.



10 The stem cells, in turn, can be coaxed to grow into a variety of cells that might one day be injected into patients.

JANA BRENNING

On the Web/*Human Cloning*

■ For updates on this breaking story, visit a special report on human cloning and stem cells at our Web site, **www.sciam.com/explorations/2001/112401ezzell/**

■ The site includes previous *Scientific American* articles on the subject as well as reports on adult stem cells and the current status of reproductive cloning projects.

the kinds of people likely to benefit from therapeutic cloning.

Our first cloning attempt occurred last July. The timing of each attempt depended on the menstrual cycles of the women who contributed eggs; the donors had to take hormone injections for several days so that they would ovulate 10 or so eggs at once instead of the normal one or two.

We had a glimmer of success in the third cycle of attempts when the nucleus of an injected fibroblast appeared to divide, but it never cleaved to form two distinct cells. So in the next cycle we decided to take the tack used by Teruhiko Wakayama and his colleagues, the scientists who created the first cloned mice in 1998. (Wakayama was then at the University of Hawaii and is now at Advanced Cell Technology.) Although we injected some of the eggs with nuclei from skin fibroblasts as usual, we injected others with ovarian cells called cumulus cells that usually nurture developing eggs in the ovary and that can be found still clinging to eggs after ovulation. Cumulus cells are so small they can be injected whole. In the end, it took a total of 71 eggs from seven volunteers before we could generate our first cloned early embryo. Of the eight eggs we injected with cumulus cells, two divided to form early embryos of four cells—and one progressed to at least six cells—before growth stopped.

Parthenogenesis

WE ALSO SOUGHT TO DETERMINE whether we could induce human eggs to divide into early embryos without being fertilized by a sperm or being enucleated and injected with a donor cell. Although mature eggs and sperm normally have only half the genetic material of a typical body cell, to prevent an embryo from having a double set of genes following conception, eggs halve their genetic complement relatively late in their maturation cycle. If activated before that stage, they still retain a full set of genes.

Stem cells derived from such parthenogenetically activated cells would be unlikely to be rejected after transplantation because they would be very similar to a patient's own cells and would not produce many molecules that would be unfamiliar to the person's immune system. (They would not be identical to the individual's cells because of the gene shuffling that always occurs during the formation of eggs and sperm.) Such cells might also raise fewer moral dilemmas for some people than would stem cells derived from cloned early embryos.

Under one scenario, a woman with heart disease might have her own eggs collected and activated in the laboratory to yield blastocysts. Scientists could then use combinations of growth factors to coax stem cells isolated from the blastocysts to become cardiac muscle cells growing in laboratory dishes that could be implanted back into the woman to patch a diseased area of the heart. Using a similar technique, called androgenesis, to create stem cells to treat a man would be trickier. But it might involve transferring two nuclei from the man's sperm into a contributed egg that had been stripped of its nucleus.

Researchers have previously reported prompting eggs from mice and rabbits to divide into embryos by exposing them to different chemicals or physical stimuli such as an electrical shock. As early as 1983, Elizabeth J. Robertson, who is now at Harvard University, demonstrated that stem cells isolated from parthenogenetic mouse embryos could form a variety of tissues, including nerve and muscle.

In our parthenogenesis experiments, we exposed 22 eggs to chemicals that changed the concentration of charged atoms called ions inside the cells. After five days of growing in culture dishes, six eggs had developed into what appeared to be blastocysts, but none clearly contained the so-called inner cell mass that yields stem cells.

Why We Did It

WE ARE EAGER FOR THE DAY when we will be able to offer therapeutic cloning or cell therapy arising from parthenogenesis to sick patients. Currently our efforts are focused on diseases of the nervous and cardiovascular systems and on diabetes, autoimmune disorders, and diseases involving the blood and bone marrow.

Once we are able to derive nerve cells from cloned embryos, we hope not only to heal damaged spinal cords but to treat brain disorders such as Parkinson's disease, in which the death of brain cells that make a substance called dopamine leads to uncontrollable tremors and paralysis. Alzheimer's disease, stroke and epilepsy might also yield to such an approach.

Besides insulin-producing pancreatic islet cells for treating diabetes, stem cells from cloned embryos could also be nudged to become heart muscle cells as therapies for congestive heart failure, arrhythmias and cardiac tissue scarred by heart attacks.

A potentially even more interesting application could involve prompting cloned stem cells to differentiate into cells of the blood and bone marrow. Autoimmune disorders such as multiple sclerosis and rheumatoid arthritis arise when white blood cells of the immune system, which arise from the bone marrow, attack the body's own tissues. Preliminary studies have shown that cancer patients who also had autoimmune diseases gained relief from autoimmune symptoms after they received bone marrow transplants to replace their own marrow that had been killed by high-dose chemotherapy to treat the cancer. Infusions of blood-forming, or hematopoietic, cloned stem cells might "reboot" the immune systems of people with autoimmune diseases.

But are cloned cells—or those generated through parthenogenesis—normal? Only clinical tests of the cells will show ultimately whether such cells are safe enough for routine use in patients, but our studies of cloned animals have shown that clones are healthy. In the November 30, 2001, issue of *Science*, we reported on our success to date with cloning cattle. Of 30 cloned cattle, six died shortly after birth, but the rest have had normal results on physical ex-

The Ethical Considerations

Advanced Cell Technology assembled a board of outside ethicists to weigh the moral implications of therapeutic cloning research, which aims to generate replacement tissues to treat a range of diseases. Here are the five major questions the board considered before the company went forward with cloning the first human embryo.

By Ronald M. Green

What is the moral status of the organisms created by cloning?
If a cloned organism were implanted into a womb, as was done in the case of Dolly the sheep, it could possibly go on to full development and birth. Because of this potential, some would argue that the organism produced in human therapeutic cloning experiments is the equivalent of any ordinary human embryo and merits the same degree of respect and protection.

Most members of our advisory board did not agree. We pointed out that, unlike an embryo, a cloned organism is not the result of fertilization of an egg by a sperm. It is a new type of biological entity never before seen in nature. Although it possesses some potential for developing into a full human being, this capacity is very limited. At the blastocyst stage, when the organism is typically disaggregated to create an embryonic stem cell line, it is a ball of cells no bigger than the period at the end of this sentence. (Embryos normally do not attach to the wall of the uterus and begin development until after the blastocyst stage.) It has no organs, it cannot possibly think or feel, and it has none of the attributes thought of as human. Although board members understood that some people would liken this organism to an embryo, we preferred the term "activated egg," and

A cloned organism is a NEW

we concluded that its characteristics did not preclude its use in work that might save the lives of children and adults.

Is it permissible to create such a developing human entity only to destroy it?
Those who believe that human life begins at conception—and who also regard activated eggs as morally equivalent to human embryos—cannot ethically approve therapeutic cloning research. For them, such research is equivalent to killing a living child in order to harvest its organs for the benefit of others. Some of those who think this way, however, might nonetheless find acceptable research on human stem cells derived from embryos left over from in vitro fertilization (IVF) procedures. They reason, rightly or wrongly, that these embryos are certain to be destroyed and that at least some good might result from using the cells. But therapeutic cloning remains totally unacceptable to such people because it involves the deliberate creation of what they deem to be a human being in order to destroy it.

Many who do not accord moral status to the entities produced by therapeutic cloning disagree with that view. Like our board members, they argue that the benefits of this research and the

MELISSA SZALKOWSKI

sensitive ethical issues in therapeutic cloning research. In each of her monthly cycles, a woman usually produces only one or two mature eggs. To increase that to a number that can be used in research, she must be given stimulatory medications such as those used in reproductive IVF procedures. In rare cases, these drugs can provoke a so-called hyperstimulation syndrome that can lead to liver damage, kidney failure or stroke. According to some studies, ovulation-stimulating drugs have also been associated with a heightened risk for ovarian cancer. The surgery to retrieve the eggs also carries risks, such as the dangers of general anesthesia and bleeding. Is it ethical to subject a woman to these risks for research purposes? If women are offered payment to undergo these risks, might that cause human reproductive material to become viewed as a commodity that can be commercialized? We do not permit the sale of human organs or babies. Are eggs any different?

In responding to these concerns, members of the board took note of two facts. First, a substantial market in human eggs for reproductive purposes already exists. Young women are being paid substantial sums to provide eggs that can help single women or couples have children. If women can undergo risks for this purpose, we asked, why should they not be allowed to undertake the same risks to further medical research that could save human lives? And if they can be paid for the time and discomfort that egg donation for reproductive purposes involves, why can't they receive reasonable payment for ovulation induction for research purposes?

Second, we noted that research volunteers often accept significant risks to advance medical knowledge. If a person can agree to undergo a dangerous malaria vaccine study to help cure disease, why should they be prevented from donating eggs for similar lifesaving research?

In the end, we concluded that it would be unduly paternalistic to prohibit women from donating eggs for this research. At the same time, we established a rigorous informed-consent procedure so that egg donors would be made fully aware of the possible dangers. We insisted that ovulation-stimulating medications be administered at safe dosages. And we set payment for participation at a modest level: $4,000 (about $40 an hour), which is roughly the average paid in New England for egg donation for reproductive purposes. We wanted to prevent payment from becoming an undue influence that could blind women to the risks.

TYPE OF BIOLOGICAL ENTITY never before seen in nature.

possible therapies it could produce far outweigh the claims of the activated eggs. Remarkably, some who share this moral view nonetheless oppose the research on symbolic grounds. They maintain that it is unseemly to create human life in any form only to destroy it. They worry that it might start society down a slippery slope that could lead to the scavenging of organs from adults without their consent.

These symbolic and "slippery slope" arguments often have powerful emotional force, but they are hard to assess. Is it really true that using activated eggs for lifesaving therapies will lead to these imagined abuses? On the contrary, if medical science can increase people's chances of healthy survival, might not this research even enhance respect for human life? Members of the board took note of the fact that the U.K., until very recently, has legally permitted the deliberate creation and destruction of human embryos in research since the early 1990s [*see box on page 51*]. There has been no apparent ill effect of this permission on British society. In the end, the symbolic and slippery slope arguments did not persuade board members that therapeutic cloning research should not go forward.

Is it right to seek human eggs for scientific research?

The need to obtain a supply of human eggs leads to one of the most

What are the ethical issues relating to the person whose cells are being cloned?

It may seem that individuals who provide the cells (usually skin fibroblasts) that are fused with enucleated eggs in therapeutic cloning research face no risk apart from the remote possibility of an infection at the site of the skin biopsy. But cloning is a controversial issue that exposes all research participants to novel risks. Cell

Cell donors might find themselves at the CENTER OF A MEDIA STORM if they are identified as having allowed themselves to be cloned.

donors, for example, might find themselves at the center of a media storm if they are identified as having allowed themselves to be cloned. To prevent this, the ethics advisory board insisted on procedures ensuring strict confidentiality for both egg and cell donors (unless they choose to come forward).

One question that occupied much of our time was whether children could donate cells for this research. We concluded that in general this is not advisable, because on reaching maturity the child may feel morally compromised by having been made to contribute to a cloning procedure. We made an exception, however, in the case of an infant with a fatal genetic disease. We knew that a stem cell line based on the child's DNA might be a powerful tool in research aimed at curing the disease. Although the child would probably not survive long enough to benefit from this research, we concluded that the parents had a right to make this decision on the child's behalf. This child's cells have not yet been used in a cloning procedure.

Will therapeutic cloning facilitate reproductive cloning, the birth of a cloned baby?

A final major question raised by this research is whether it will hasten the day when people undertake human reproductive cloning. This concern presumes that reproductive cloning is and always will be ethically wrong. Many who hold this view cite the incidence of deaths and birth defects in cloned animals. Others worry about more remote dangers. They point to possible psychological risks to children produced in families in which a parent may also be a child's genetic twin. They fear that cloned children may face unrealistic expectations to live up to the achievements of their genetic predecessor. And they worry about possible social risks of cloning if societies decide to replicate a limited number of desired genomes on a large scale for military or other purposes. In opposition to this, some people hail the prospect of cloning. They see it as a new way to provide biologically related offspring for some infertile couples or as a means of reducing the risks of some inherited genetic diseases.

Whatever one thinks about the ethics of reproductive cloning, placing a ban on therapeutic cloning will not make reproductive cloning less likely. Although therapeutic cloning could help scientists perfect techniques for reproductive cloning, it could also make much clearer the dangers of trying to produce a human being in this way. There is already evidence that some cloned animals can experience improper gene expression and disruptions in imprinting, the normal pattern of silencing genes not needed in particular tissues. Such problems could discourage prospective parents from using this technology to have a baby. Thus, therapeutic cloning research could actually reduce the likelihood that cloning would be seen as a viable reproductive option.

A ban on therapeutic cloning also would not prevent unsupervised researchers from going ahead with reproductive cloning efforts on their own. Groups such as the Raëlians, a religous cult, or renegade scientists such as Richard G. Seed, a physicist based in Riverside, Ill., who has also been involved in embryology, have announced their intent to clone a human being and presumably will try to do so regardless of whether therapeutic cloning research is banned. A ban on therapeutic cloning will block useful research while allowing less responsible people to try reproductive cloning wherever they can find a permissive legal environment. By shutting down responsible research on the cell biology of human cloning, such a ban would also guarantee that the first efforts at cloning a human being would be based on scanty scientific information.

Our ethics board has had to wrestle with new and challenging questions, but we believe we have managed to give Advanced Cell Technology a firm ethical base for its therapeutic cloning research program. After researchers derive stem cells from cloned human activated eggs, ethicists will need to determine at what point it will be safe to try to transplant such cells back into volunteer donors. The tasks ahead for ethics boards like ours are demanding. The reward is assisting at the cutting edge of medical knowledge.

RONALD M. GREEN is director of the Ethics Institute at Dartmouth College and chair of the ethics advisory board of Advanced Cell Technology in Worcester, Mass.

Other current board members are Judith Bernstein of Boston University ; Susan Crockin, a health care lawyer in private practice in Newton, Mass.; Kenneth Goodman, director of the Forum for Bioethics at the University of Miami; Robert Kaufmann of the Southeastern Fertility Center in Mount Pleasant, S.C.; Susan R. Levin, a counselor in private practice in West Roxbury, Mass.; Susan L. Moss of San Diego State University; and Carol Tauer of the Minnesota Center for Health Care Ethics. Michael D. West, president and CEO of Advanced Cell Technology, is an ex officio member of the ethics advisory board.

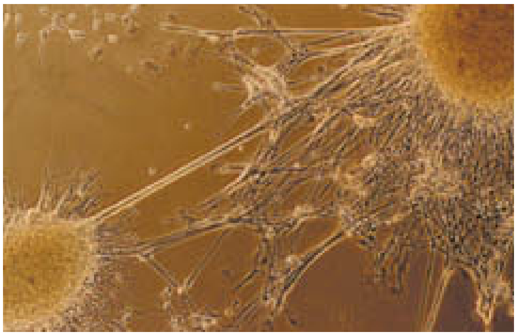
Cloning and the Law

Will therapeutic cloning end up being against the law?

Legislative activities threaten to stand in the way of the medical benefits that therapeutic cloning could provide. On July 31, 2001, the House of Representatives voted for a broad ban on human cloning that would not only prohibit the use of cloning for reproduction but would also prohibit cloning for research purposes, such as to derive stem cells that could be used in therapies. The legislation, which was sponsored by Representatives David Weldon (R-Fla.) and Bart Stupak (D-Mich.), would carry penalties of up to 10 years in prison and fines of $1 million for anyone who generates cloned human embryos. An amendment introduced by Representative Jim Greenwood (R-Pa.) that would have allowed therapeutic cloning failed. (Greenwood has his own pending bill on the subject that would outlaw only reproductive cloning.) Such laws would affect all scientists in the U.S., not only those working with government funding.

The Weldon/Stupak bill has now been referred to the Senate, which is expected to take up the issue in early 2002. Senator Sam Brownback (R-Kan.), who has also introduced a bill, opposes human cloning for any purpose. He tried to add amendments banning human cloning to the fiscal 2002 spending bill for the Department of Health and Human Services last November. Such measures face an uphill battle, however, in the Democrat-controlled Senate. The Bush administration supports a total cloning ban and has endorsed the Weldon/Stupak bill.

The matter of human cloning is also being taken up once again by the U.K. Parliament. In 2000 the U.K. altered its Human Fertilization and Embryology Act of 1990 to specifically allow human therapeutic cloning. But last November antiabortion activists succeeded in having the provision struck down on the grounds that cloning does not involve an embryo created by the union of an egg and a sperm and therefore cannot be included under the act.


JOSE B. CIBELLI

PRIMATE NERVE CELLS derived from stem cells growing in culture look like normal nerve cells.

In a related issue, last August President George Bush barred the use of federal funds for research involving stem cells derived from embryos, including those generated using cloning. The bar permits federally funded scientists to experiment only with stem cell cultures, or lines, created before the August announcement. But many scientists have criticized the quality and availability of these stem cell lines. Others claim that without cloning, stem cells have no promise, because they would probably be rejected as foreign by a patient's immune system.

Legislative attempts by Senator Arlen Specter (R-Pa.) in November that would have allowed scientists to use government money to make new stem cell lines were squelched when Brownback threatened to counter with a total ban on human stem cell research.

—Carol Ezzell

ams, and tests of their immune systems show they do not differ from regular cattle. Two of the cows have even given birth to healthy calves.

The cloning process also appears to reset the "aging clock" in cloned cells, so that the cells appear younger in some ways than the cells from which they were cloned. In 2000 we reported that telomeres—the caps at the ends of chromosomes—from cloned calves are just as long as those from control calves. Telomeres normally shorten or are damaged as an organism ages. Therapeutic cloning may provide "young" cells for an aging population.

A report last July by Rudolf Jaenisch of the Whitehead Institute for Biomedical Research in Cambridge, Mass., and his colleagues gained much attention because it found so-called imprinting defects in cloned mice. Imprinting is a type of stamp placed on many genes in mammals that changes how the genes are turned on or off depending on whether the genes are inherited from the mother or the father. The imprinting program is generally "reset" during embryonic development.

Although imprinting appears to play an important role in mice, no one yet knows how significant the phenomenon is for humans. In addition, Jaenisch and his co-workers did not study mice cloned from cells taken from the bodies of adults, such as fibroblasts or cumulus cells. Instead they examined mice cloned from embryonic cells, which might be expected to be more variable. Studies showing that imprinting is normal in mice cloned from adult cells are currently in press and should be published in the scientific literature within several months.

Meanwhile we are continuing our therapeutic cloning experiments to generate cloned or parthenogenetically produced human embryos that will yield stem cells. Scientists have only begun to tap this important resource. SA

MORE TO EXPLORE

Human Therapeutic Cloning. Robert P. Lanza, Jose B. Cibelli and Michael D. West in *Nature Medicine,* Vol. 5, No. 9, pages 975–977; September 1999.

Prospects for the Use of Nuclear Transfer in Human Transplantation. Robert P. Lanza, Jose B. Cibelli and Michael D. West in *Nature Biotechnology,* Vol. 17, No. 12, pages 1171–1174; December 1999.

The Ethical Validity of Using Nuclear Transfer in Human Transplantation. Robert P. Lanza et al. in *Journal of the American Medical Association,* Vol. 284, No. 24; December 27, 2000.

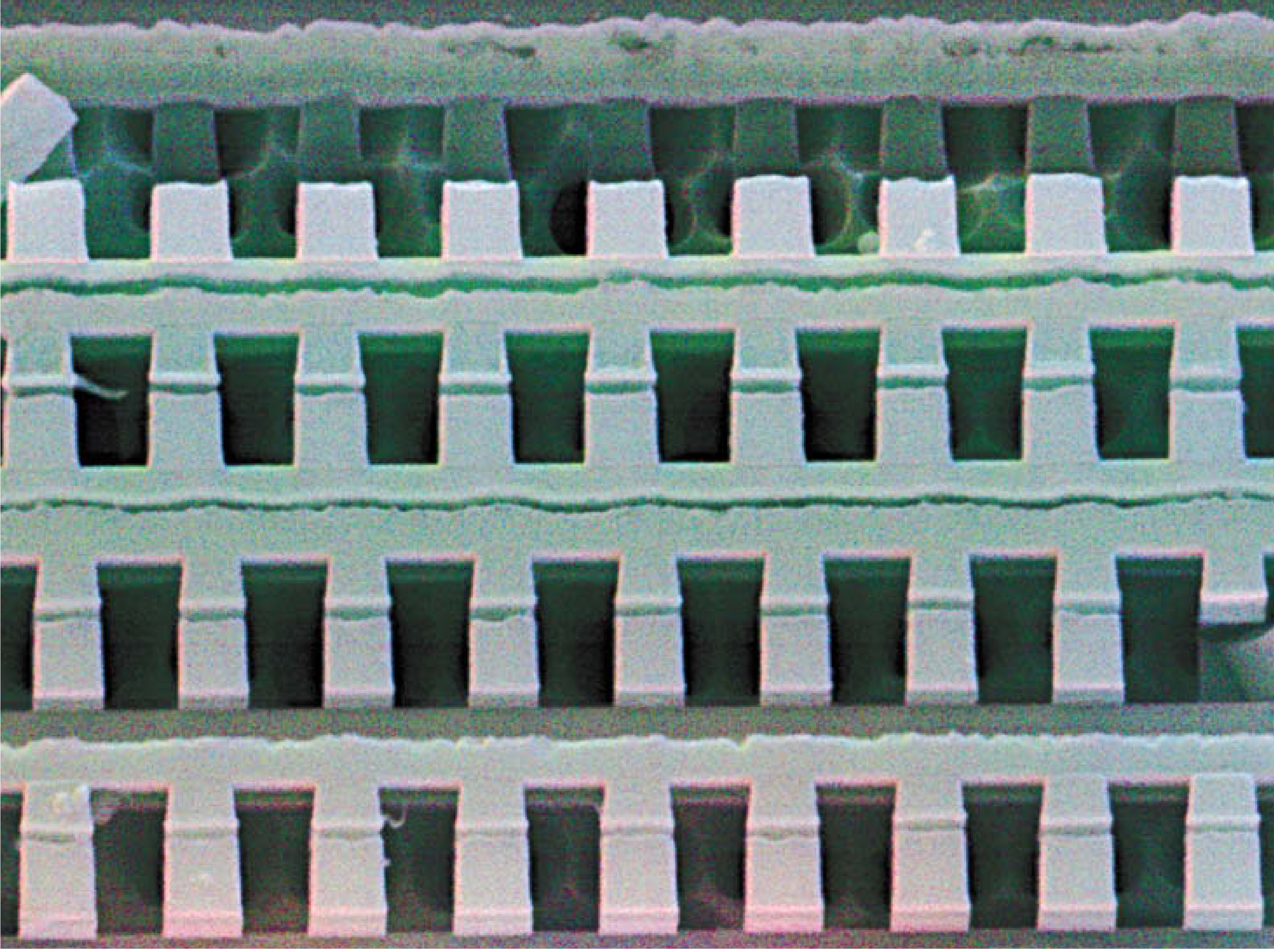
The Human Embryo Research Debates: Bioethics in the Vortex of Controversy. Ronald M. Green. Oxford University Press, 2001.

The full text of our article in *e-biomed: The Journal of Regenerative Medicine* can be viewed at **www.liebertpub.com/ebi**

a Vertical Leap for Microchips

Engineers have discovered a way to pack more computing power into microcircuits: build them vertically as well as horizontally

By Thomas H. Lee



The city of San Francisco stretches over 45 square miles—about twice the area of the island of Manhattan. Yet the economic output of Manhattan dwarfs that of San Francisco. A principal reason for the disparity is that offices in earthquake-prone California tend to spread their workers and machines close to ground level, whereas businesses in New York are stacked vertically into the skies. By building upward rather than outward, developers increase not only the value of their real estate but also the working power of the city as a whole.

An analogous strategy applied to the microscopic world of computer chips could rejuvenate a semiconductor industry that has recently begun to show signs of senescence. Surprisingly, of the more than 100 quadrillion transistors that Intel co-founder Gordon E. Moore estimates have been produced to date, nearly every one has been built on the "ground level," directly on the surface of silicon crystals. Engineers have accomplished a fantastically regular doubling of transistor density per microchip—we call it Moore's Law in the industry—simply by expanding the area of each chip and shrinking the size of each transistor. This is like building only shopping malls and no skyscrapers.

VERTICAL STACK of memory cells can store eight bits of information in the area usually allotted to just one bit. Such "3-D" microchips are set to dramatically reduce the cost of digital memory.

That is about to change. For one thing, physicists tell us that Moore's Law will end when the gates that control the flow of information inside a chip become as small as the wavelength of an electron (on the order of 10 nanometers in silicon), because transistors then cease to "transist." And many intimidating technical obstacles loom between the current state of the art and that fundamental limit. The trajectory of progress has already begun to droop.

Fortunately, I and other engineers have recently found a way to skirt some of those obstacles, to give Moore's Law a new breath of life and even to accelerate the delivery of more computing power for less cost. We have shown that it is feasible to make chips that contain vertical microcircuits using the same semiconductor foundries, the same standard materials and similar techniques to those used to manufacture conventional computer chips.

Such "three-dimensional" chips are now being commercialized by Matrix Semiconductor, a company I co-founded in

DAVID SCHARF

1998 in Santa Clara, Calif., with computer scientist P. Michael Farmwald and chip design expert Mark C. Johnson. Sometime in the first half of 2002, 3-D memory circuits will hit the market. They will be just the first of a new generation of dense, inexpensive chips that promise to make digital recording media both cheap and convenient enough to replace photographic film and audiotape. In laboratories at Stanford University and Matrix, we have also created prototype devices that incorporate vertical logic circuits. There seems to be good reason to expect that even for microprocessors, the sky is the limit.

This year **3-D memory circuits** will hit the market, just the first of a new generation of dense, inexpensive chips that promise to replace photographic **film** and **audiotape**.

The Fences of Flatland

TODAY'S STATE-OF-THE-ART microcircuits are not entirely two-dimensional. Intel's Pentium 4 processor, for example, boasts seven layers of wiring, embedded within patterns of insulating material. It is only on the bottom layer of pure silicon, however, that the active semiconducting regions lie.

So far the industry has managed to sustain Moore's Law largely by improving the way it uses that silicon wafer. Materials scientists have invented ways to grow giant crystals of silicon 30 centimeters in diameter that contain less than one part per billion of impurities. Clean-room robots shoot carefully metered doses of ions into wafers cut from these crystals. A process called photolithography defines the ion-activated regions with patterns of light and acid etching to make transistors [*see illustration on opposite page*]. To cram more transistors onto one wafer requires light of ever shorter wavelength. Mercury vapor lamps have been replaced by deep-ultraviolet excimer lasers that inscribe 130-nanometer features and can put a billion transistors on a chip. Further improvement should push that limit to 65 nanometers and perhaps 16 billion transistors.

The road beyond that point may be rough, however. Extreme ultraviolet lithography systems that use even shorter wavelengths are just now beginning to function in the laboratory. They still pose many significant problems [see "Getting More from Moore's," by Gary Stix; SCIENTIFIC AMERICAN, April 2001].

If history is any guide, engineers will probably clear these hurdles; the economic incentive to do so is huge. But as the number of obstacles increases, the pace of progress may slow considerably. The official "road map" published by the Semiconductor Industry Association projects that chips will grow 4 to 5 percent a year in area; historically, area has grown about 15 percent a year. The periodic 30 percent reduction in minimum feature size is probably now going to occur every three years instead of every two. Even at this slower pace, Moore's Law will most likely hit fundamental limits sometime between 2010 and 2020.

One important factor has remained roughly constant: the cost of semiconductor real estate, at about $1 billion per acre of processed silicon. So why haven't silicon developers taken the seemingly obvious step of building upward? The simplest reason is that transistors are fastest and most reliable only when formed from the perfectly aligned atoms of a wafer cut from a single crystal of silicon.

Once we coat that semiconducting wafer with an insulating oxide or metal wires, there is no known way to recover the underlying crystalline pattern—it's like trying to match the pattern of a parquet floor after it has been covered with carpet. Silicon deposited onto a noncrystalline surface tends to be completely disordered and amorphous. With appropriate heat treatment, we can encourage the silicon to form minuscule islands ("grains") of single crystals, but the ordered lines of atoms collide abruptly at odd angles at the boundaries between grains. Contaminants can pile up at these barriers and short out any transistor or memory cell caught in the middle. For many years, such amorphous and polysilicon (short for polycrystalline silicon) devices were so poor that no one seriously considered them for anything more sophisticated than solar cells.

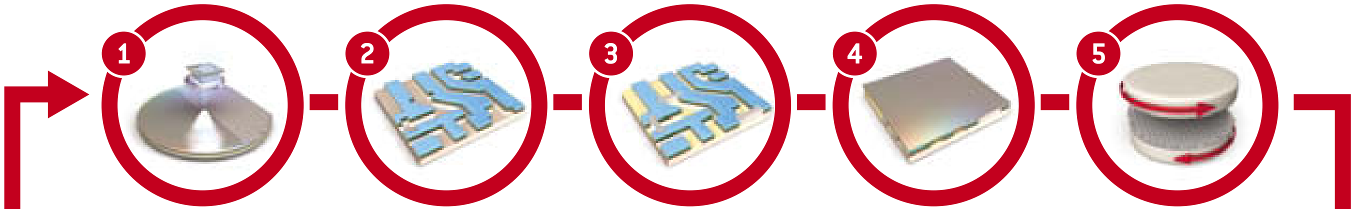
In the early 1980s, however, premature worries that Moore's Law was about to fail stimulated a flurry of attempts to make 3-D microcircuits in which the transistors spanned vertical towers—rather than horizontal bridges—of silicon. James F. Gibbons and others at Stanford used laser beams to

Overview/3-D Microcircuits

- Moore's Law—the steady growth in silicon-based microchip complexity on which the information technology industry depends—is approaching fundamental physical limits. Switching from silicon to new kinds of semiconductors would be enormously expensive.
- Engineers recently have found a way to extend and perhaps accelerate Moore's Law significantly. They have designed and mass-produced multilayered chips in which the semiconducting parts of circuits are no longer confined to a single plane but extend vertically as well.
- The first products incorporating such 3-D microchips—memory cards cheap enough to use as digital film and audio-recording media—are scheduled to appear later this year.

GOING 3-D: SAME EQUIPMENT, DIFFERENT STEPS

HOW 2-D CHIPS ARE MADE

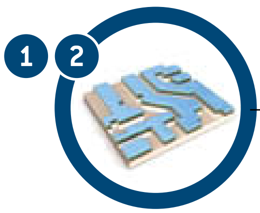


1. Patterns of ultraviolet light are focused onto a silicon wafer coated with photoresist
2. Exposed photoresist is removed, and unprotected areas are etched away by gases
3. Ions are showered onto the wafer, doping areas of exposed silicon to make transistors
4. The wafer is coated with insulating dielectric or conducting metal
5. Chemical-mechanical polishing flattens the wafer's surface with 50-nanometer precision

PROCESS IS REPEATED FOUR OR MORE TIMES TO ADD METAL INTERCONNECTIONS AND INSULATING OXIDES

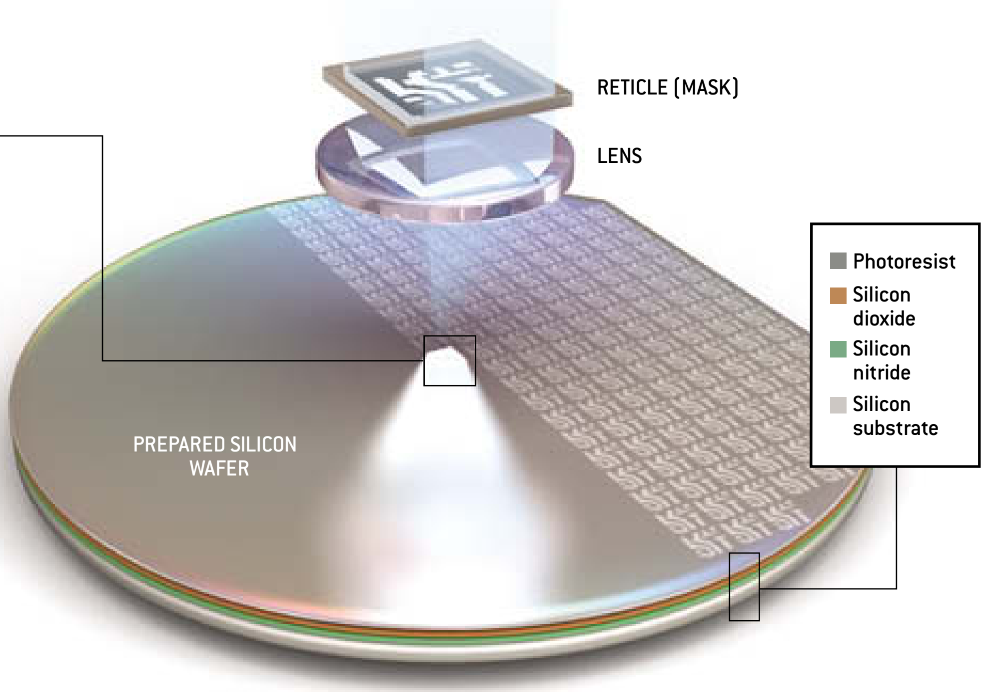
HOW 3-D CHIPS ARE MADE

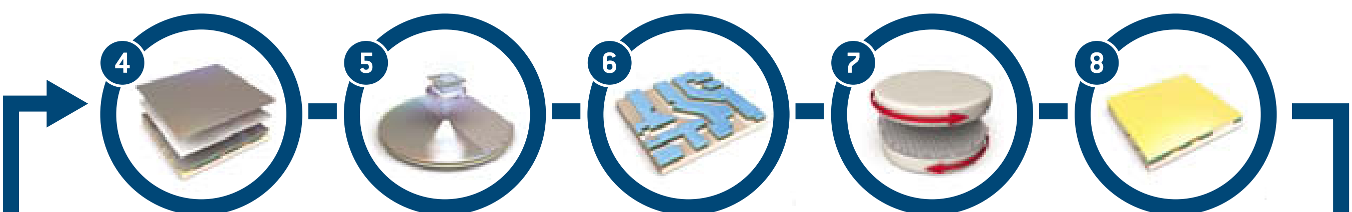
Additional steps using the same equipment and materials create 3-D microcircuits with many polysilicon transistors stacked vertically



Photolithography and etching proceed just as for 2-D chips, above

Ion implantation dopes the silicon to create transistors

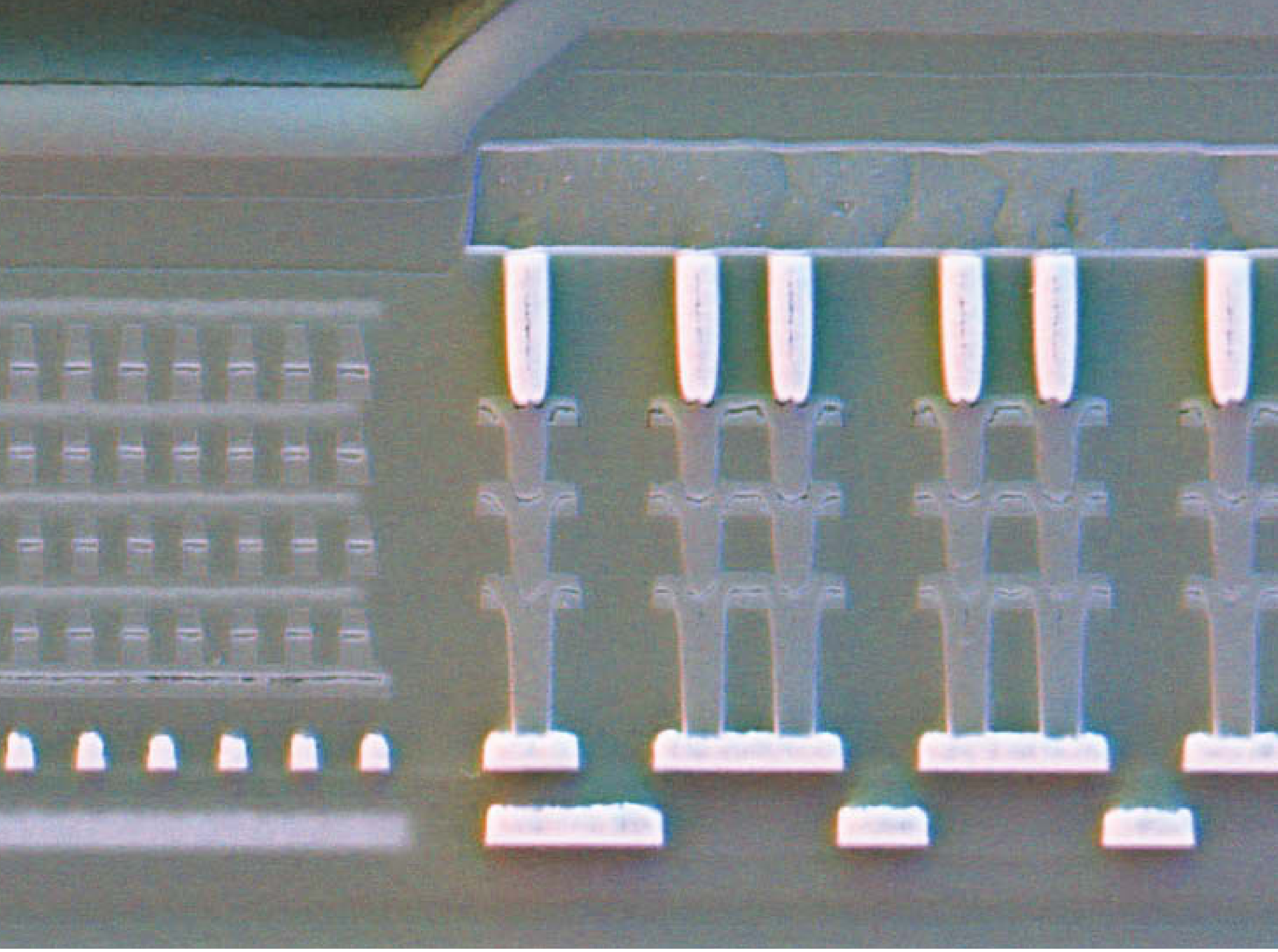




4. Three new layers are added: polysilicon, tungsten metal and then more polysilicon
5. Photolithography is repeated to create active regions of polysilicon
6. Memory cells and metal interconnections are etched; insulation is added
7. Chemical-mechanical polishing knocks down any high spots
8. A layer of "antifuse" material is added; burning out an antifuse will store a bit in the memory

PROCESS IS REPEATED NINE TIMES TO STACK EIGHT MEMORY CELLS ON TOP OF ONE ANOTHER

JOE ZEFF



LAYERS OF POLYSILICON that form the honeycomb of memory cells (*left*) are interconnected by "vias" (*vertical columns at right*). These are connected in turn by tungsten wires (*bright structures*).

DAVID SCHARF

improve the quality of silicon films deposited onto nonsilicon substrates. Others tried stacking conventional 2-D chips on top of one another. Regrettably, the former approach was too slow and the latter was too expensive to be economically competitive. Traditional chipmaking stayed on track, and engineers stopped thinking much about vertical circuits.

A New Use for Old Tools

IN 1997 FARMWALD and I started exploring 3-D chips again and realized that two key enabling technologies, developed for other purposes, made 3-D circuits truly practical for the first time. One was a technique to lay down polysilicon so that each island of a single crystal is large enough to encompass many memory cells or transistors. The second advance was a way to flatten each coat of new material so that the chips don't rise unevenly like towers built by drunken bricklayers.

We can thank the flat-panel-display industry for the first breakthrough. Its engineers figured out how to make millions of transistors from a thin film spread over a large, amorphous substrate (glass, in their case; other materials in ours). Thin-film transistors now populate the display panels of virtually every laptop computer. Part of the secret is to deposit the silicon at about 400 degrees Celsius as an extremely smooth (though amorphous) film, then to cook the entire wafer uniformly above about 500 degrees C for a few minutes. This converts the film to polysilicon with regular crystalline regions of a micron or more in diameter. Although LCD panels require only a single layer of transistors, the same machines that make the panels can also manufacture multilayer devices.

THE AUTHOR

THOMAS H. LEE worked as a circuit designer at Analog Devices in 1990, after receiving his doctorate from the Massachusetts Institute of Technology. In 1992 he joined Rambus to develop high-speed analog circuitry for memory chips. His work was also incorporated into microprocessors made by Advanced Micro Devices and Digital Equipment Corporation. In 1994 Lee joined the electrical engineering faculty at Stanford University, where his research focus has been on gigahertz communication circuits. He is a Distinguished Lecturer of two professional societies and a Packard Fellow and has been granted 14 U.S. patents, including four for constructing and mass-producing 3-D integrated circuits.

The second key enabling advance, called chemical-mechanical polishing (or CMP), emerged from IBM's research labs in the late 1980s. Back then, chip designers considered it risky to add two or three layers of metal on top of the silicon wafer because each new layer added hills and valleys that made it difficult to keep photolithographic patterns in focus.

To eliminate the bumps in each layer, process technologists adapted a trick that lens makers use to polish mirrors. The basic technique was used on all Intel 80486 processors: after each coating of silicon, metal or insulating oxide is added, the wafer is placed facedown on a pad. Spindles then rotate the pad and wafer in opposite directions while a slurry of abrasives and reactive alkaline chemicals passes in between. After mere minutes of polishing, the wafer is flat to within 50 nanometers, an ideal substrate for further processing. With advances in CMP machines, seven and eight layers of metal have become common in microchip designs; patience seems to be the main limiting factor in adding still more layers.

Building directly on these 2-D technologies, we have made 3-D circuits by coating standard silicon wafers with many successive layers of polysilicon (as well as insulating and metallic layers), polishing the surface flat after each step. Although electrons do not move quite as easily in polysilicon as they do in the single-crystal kind, research has produced 3-D transistors with 90 to 95 percent of the electron mobility seen in their 2-D counterparts.

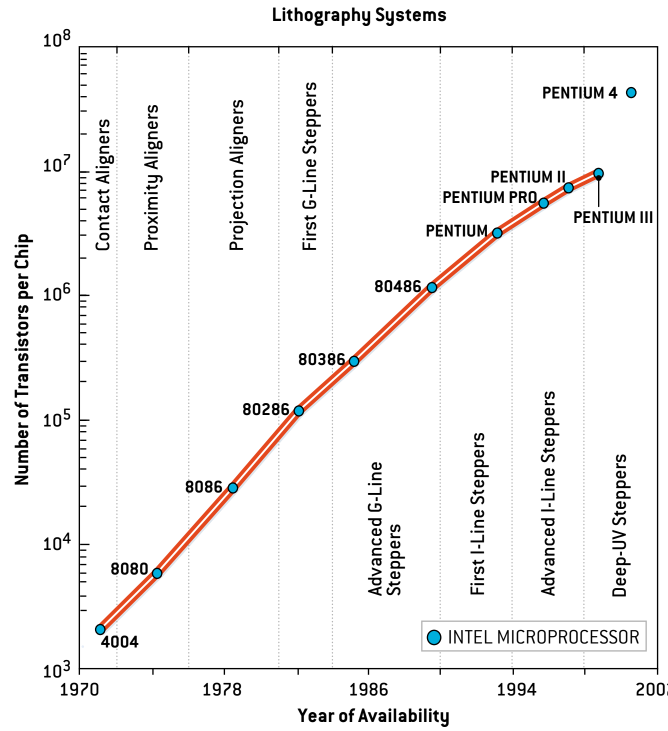
Stacking devices vertically offers a way around some of the weighty obstacles that threaten to derail Moore's Law. As shopping-mall-style chips continue to sprawl outward, for example, it becomes increasingly hard to keep the photolithographic image in focus at the edges. And the relatively long wires that connect far-flung sections of conventional microprocessors cause delays that reduce performance and complicate design.

Ever shrinking circuits pose other problems. Transistors depend critically on a thin insulating layer below the control electrode. In the most advanced 2-D chips, this layer of silicon dioxide insulation measures just three nanometers—about two dozen atoms—in thickness. From transistor to transistor, that thickness must not vary by more than one or two atoms. The industry routinely meets this challenge, because it is much easier to grow superthin films than it is to etch supernarrow channels. But there may be no practical way to make these insulating layers much thinner, because current flow by quantum tunneling makes them progressively worse insulators. It's likely that some other material will soon have to replace silicon dioxide, but toolmakers have yet to agree on what that material will be.

There have been many novel chip designs proposed to address these problems. Most depend on replacing silicon altogether with various exotic materials, such as organic polymers, carbon fullerenes, copper compounds, ferroelectrics or magnetic alloys. But to abandon silicon is to squander an enormously valuable foundation of knowledge constructed

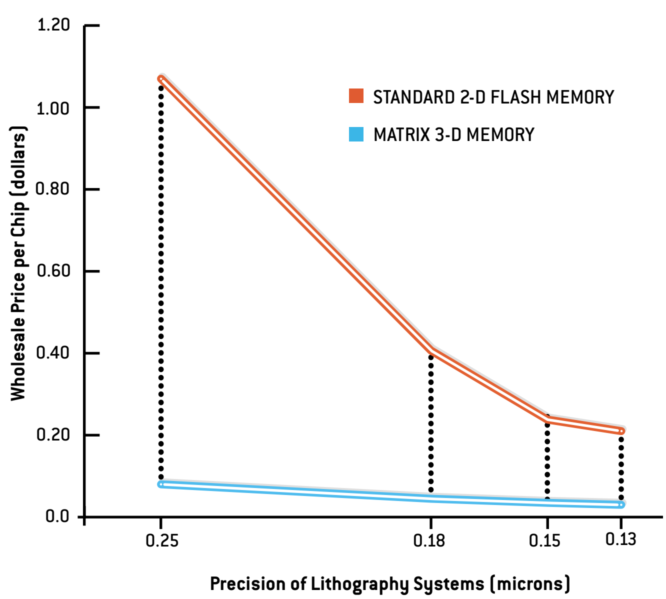
MOORE'S LAW—the periodic increase in microchip complexity—slowed around 1990 as engineers struggled to invent photolithography systems that etch ever smaller structures into silicon (*top*). Although architectural changes boosted the size and number of gates in the Pentium 4, Moore's Law will likely slow further as lithography systems move from ultraviolet light toward x-rays, which are much harder to focus. By increasing the vertical complexity of microcircuits, however, chip designers can achieve the same computing power at far lower cost (*bottom*).

EACH NEW ADVANCE IN CHIPMAKING ...



SOURCES: VLSI Research, Inc.; Integrated Circuit Engineering Corporation; Intel

... LOWERS THE COST PER CHIP



NINA FINKEL

Vertical electronics can reduce manufacturing costs 10-fold or more, and the density of 3-D devices should increase at least as fast as Moore's Law as we add layers.

over 50 years with some $100 billion worth of investment.

The 3-D electronic design process, in contrast, introduces no new atoms and leverages the huge industry investment in thin-film and CMP equipment. Because it is so expensive to produce and process ultrapure silicon ingots, the cost of silicon is largely proportional to the area (not the volume) consumed. So vertical electronics can reduce manufacturing costs 10-fold or more compared with traditional chips. And the density of 3-D devices should increase at least as fast as Moore's Law as we add more and more layers.

Digital Film and Beyond

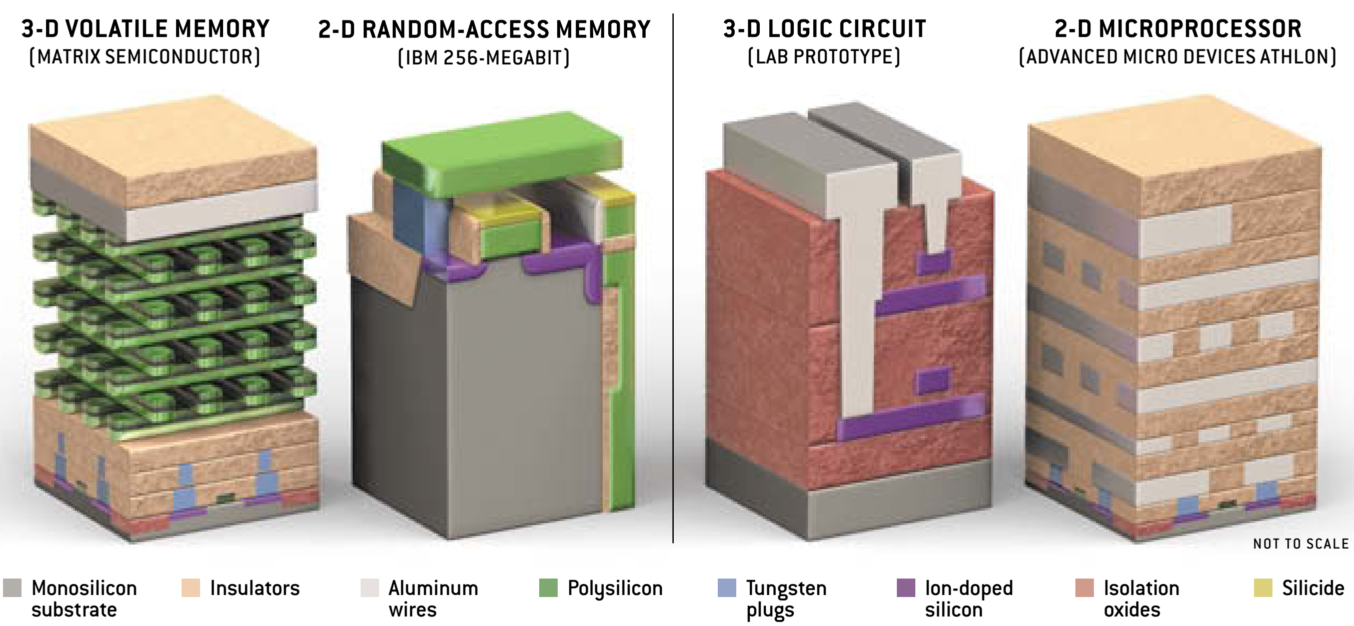
TRADITIONALLY, semiconductor companies have worked the bugs out of new fabrication processes by making memory devices before attempting to mass-produce more complicated chips such as logic circuits. Memories are vast arrays of fundamentally simple cells, so there are fewer skills to master and fewer problems to solve.

That is the approach we at Matrix will take later this year as we introduce a 3-D memory chip in which the cells are stacked eight high [*see illustration below*]. Unlike the RAM memories used in PCs, these chips use exceedingly simple memory cells that make them more like film, indelible once written. They are intended to be a low-cost medium for digital photography and audio. With 512 million memory cells, this first vertical microchip has enough capacity to store more than an hour of high-quality audio (through data compression) and a few hundred photographs (each comprising about one million pixels). The capacity will rise, and the unit cost will fall, over time. We have already proved that 12-cell-high devices are feasible, and 16-layer chips seem well within reach.

We have also demonstrated much more complex 3-D microcircuits in the laboratory, including static RAM, logic gates and even erasable EPROM memories. Although they are in very early stages of development, these basic building blocks are all that is needed to recast any planar circuit—including dynamic RAM, nonvolatile memories, wireless transceivers, and microprocessors—in 3-D form. Stood on end, the transistors in such circuits could be quite tiny because their channels will be made from thin films that are 10 times as precise as channels defined by ultraviolet light.

As with all engineering advances, this new manufacturing technique has limitations and trade-offs. Some fraction of memory cells or transistors in a vertical microcircuit will happen to straddle a boundary between polysilicon grains and will possibly fail as a result. We will have to use error detection and correction routines, like those used with audio CDs, and find ways to route signals around defective paths. The strategies of fault-tolerant computing, though well known, have generally

INTERIOR STRUCTURE of 3-D chips is dramatically different from those of conventional, 2-D memories and microprocessors. In standard logic and memory chips, all the transistors in the circuit are confined to a single crystalline layer of silicon. In 3-D microcircuits, transistors or memory cells are formed within multiple layers of silicon.



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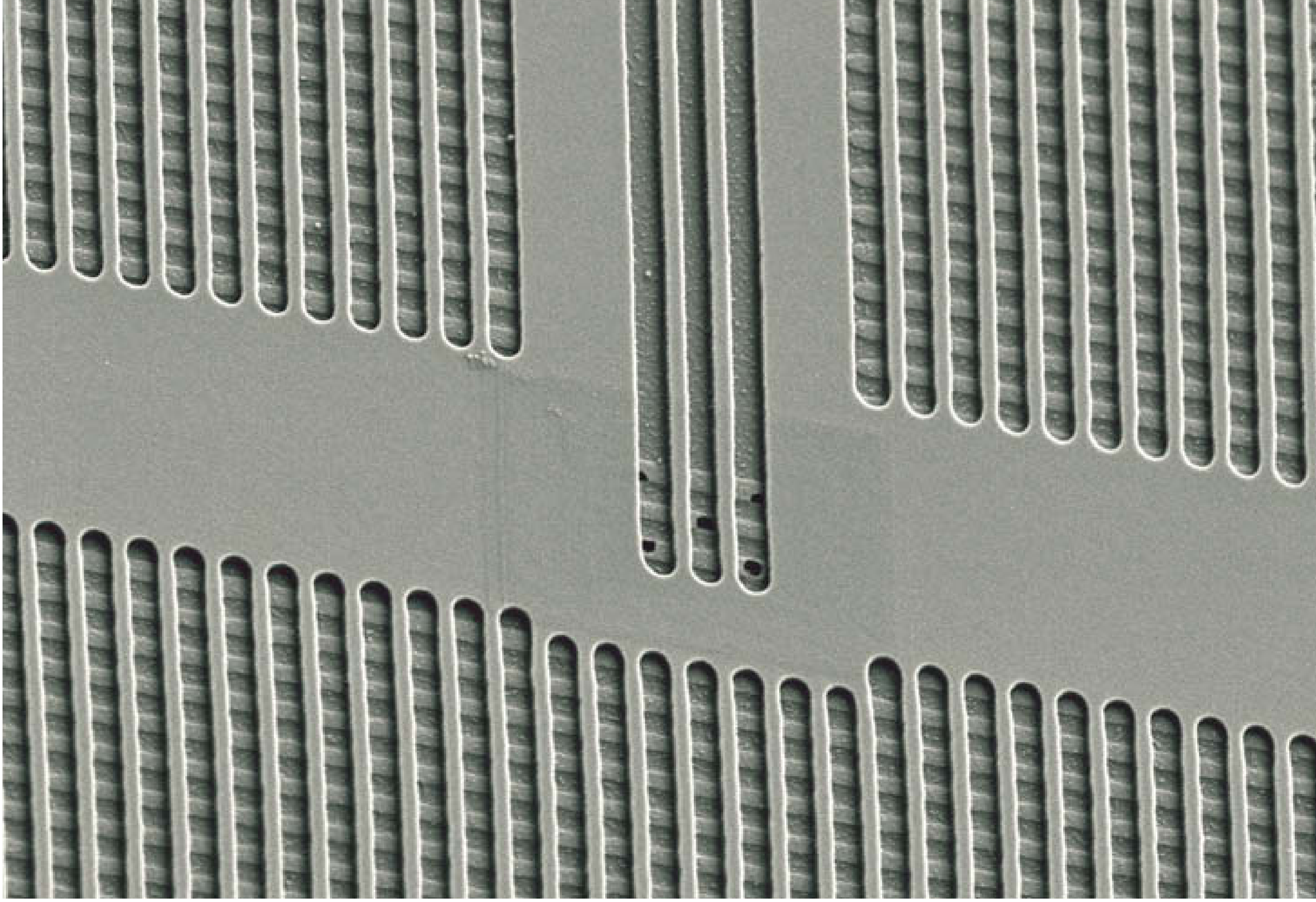

BITS ARE STORED permanently in this 3-D memory chip when antifuses are blown (*dark spots in center*), connecting two halves of a circuit.

MATRIX SEMICONDUCTOR

not been built into microchips themselves. Such techniques are unnecessary and too cumbersome for application in most planar contexts, but the cost reductions afforded by 3-D processing fortuitously make the remedial technology economically feasible precisely when it becomes necessary.

Speed is another trade-off. Modern thin-film transistors typically perform at about half the speed of monocrystalline devices, although the difference is smaller when you compare entire circuits, because components packed in three dimensions need considerably shorter wires. Numerous researchers are investigating ways to close that gap further.

Beyond those special considerations, 3-D chips face essentially the same challenges as do conventional planar electronics—certain problems just appear sooner because of the effective acceleration of Moore's Law. Heat may be the most acute issue for dense 3-D devices because of their smaller surface area. The power density of a modern microprocessor already exceeds that of the burner on a typical stove. Ineffectiveness of current strategies for dissipating all that heat, such as reducing voltages or selectively activating only parts of a circuit, may limit the performance of dense 3-D circuits unless more advanced cooling technology is used. Fortunately, the newest microrefrigerators can now remove 200 watts per square millimeter while consuming only about one watt. Thermal limits are thus not yet fundamental impediments.

There is certainly lots of room for improvement. The fluid-cooled human brain, whose dimensions considerably exceed those of any 3-D circuit currently contemplated, dissipates a mere 25 watts; a 2.2-square-centimeter Pentium 4 microprocessor, in contrast, consumes about 80 watts. Although we cannot rule out the possibility that the inability to solve the heat problem may ultimately impose harsh limits on what 3-D circuits can do, history suggests that the strong economic incentives at play will eventually spark creative solutions.

Enabling Moore's Law to continue even a few years longer than it otherwise would have will have far-reaching consequences. For 30 years, chip manufacturers have striven constantly to print ever smaller structures within a single plane. It seems inevitable that in the future we will scale microcircuits vertically as well as horizontally. The technology is both possible and practical, and the benefits are far too compelling to ignore. SA

MORE TO EXPLORE

The Solid-State Century. *Scientific American* Special Issue, Vol. 8, No. 1; October 1997.

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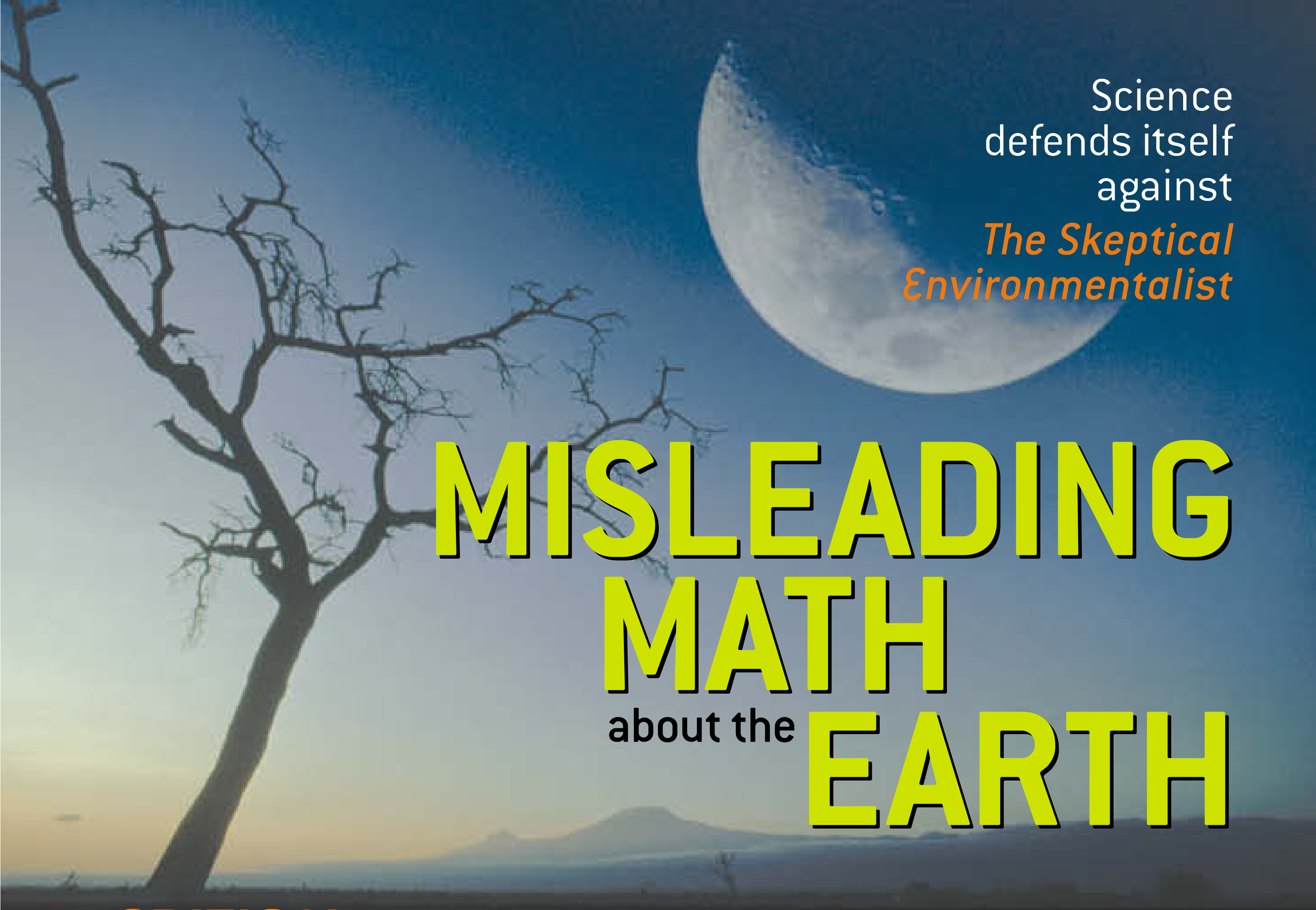


Science defends itself against *The Skeptical Environmentalist*

MISLEADING MATH about the EARTH

CRITICAL thinking and hard data are cornerstones of all good science. Because environmental sciences are so keenly important to both our biological and economic survival—causes that are often seen to be in conflict—they deserve full scrutiny. With that in mind, the book *The Skeptical Environmentalist* (Cambridge University Press), by Bjørn Lomborg, a statistician and political scientist at the University of Aarhus in Denmark, should be a welcome audit. And yet it isn't.

As the book's subtitle—*Measuring the Real State of the World*—indicates, Lomborg's intention was to reanalyze environmental data so that the public might make policy decisions based on the truest understanding of what science has determined. His conclusion, which he writes surprised even him, was that contrary to the gloomy predictions of degradation he calls "the litany," everything is getting better. Not that all is rosy, but the future for the environment is less dire than is supposed. Instead Lomborg accuses a pessimistic and dishonest cabal of environmental groups, institutions and the media of distorting scientists' actual findings. (A copy of the book's first chapter can be found at www.lomborg.org)

The problem with Lomborg's conclusion is that the scientists themselves disavow it. Many spoke to us at SCIENTIFIC AMERICAN about their frustration at what they described as Lomborg's misrepresentation of their fields. His seemingly dispassionate outsider's view, they told us, is often marred by an incomplete use of the data or a misunderstanding of the underlying science. Even where his statistical analyses are valid, his interpretations are frequently off the mark—literally not seeing the state of the forests for the number of the trees, for example. And it is hard not to be struck by Lomborg's presumption that he has seen into the heart of the science more faithfully than have investigators who have devoted their lives to it; it is equally curious that he finds the same contrarian good news lurking in *every* diverse area of environmental science.

We asked four leading experts to critique Lomborg's treatments of their areas—global warming, energy, population and biodiversity—so readers could understand why the book provokes so much disagreement. Lomborg's assessment that conditions on earth are generally improving for human welfare may hold some truth. The errors described here, however, show that in its purpose of describing the real state of the world, the book is a failure.

John Rennie, EDITOR IN CHIEF

GERRY ELLIS *Minden Pictures*

Stephen Schneider

GLOBAL WARMING:
NEGLECTING THE COMPLEXITIES

For three decades, I have been debating alternative solutions for sustainable development with thousands of fellow scientists and policy analysts—exchanges carried out in myriad articles and formal meetings. Despite all that, I readily confess a lingering frustration: uncertainties so infuse the issue of climate change that it is still impossible to rule out either mild or catastrophic outcomes, let alone provide confident probabilities for all the claims and counterclaims made about environmental problems.

Even the most credible international assessment body, the Intergovernmental Panel on Climate Change (IPCC), has refused to attempt subjective probabilistic estimates of future temperatures. This has forced politicians to make their own guesses about the likelihood of various degrees of global warming. Will temperatures in 2100 increase by 1.4 degrees Celsius or by 5.8? The difference means relatively adaptable changes or very damaging ones.

Against this background of frustration, I began increasingly to hear that a young Danish statistician in a political science department, Bjørn Lomborg, had applied his skills in statistics to better determine how serious environmental problems are. Of course, I was anxious to see this highly publicized contribution—*The Skeptical Environmentalist: Measuring the Real State of the World.* A "skeptical environmentalist" is certainly the best kind, I mused, because uncertainties are so endemic in these complex problems that suffer from missing data, incomplete theory and nonlinear interactions. But the "*real* state of the world"—that is a high bar to set, given the large range of plausible outcomes.

And who is Lomborg, I wondered, and why haven't I come across him at any of the meetings where the usual suspects debate costs, benefits, extinction rates, carrying capacity or cloud feedback? I couldn't recall reading any scientific or policy contributions from him either. But there was this massive 515-page tome with a whopping 2,930 endnotes to wade through. On page xx of his preface, Lomborg admits, "I am not myself an expert as regards environmental problems"—truer words are not found in the rest of the book, as I'll soon illustrate. I will report primarily on the thick global warming chapter and its 600-plus endnotes. That kind of deadweight of detail alone conjures at least the trappings of comprehensive and careful scholarship. So how does the reality of the text hold up to the pretense? I'm sure you can already guess, but let me give some examples to make clear what I learned by reading.

The climate chapter makes four basic arguments:

Climate science is very uncertain, but nonetheless the real state of the science is that the sensitivity of the climate to carbon dioxide will turn out to be at the low end of the IPCC uncertainty range—which is for a warming of 1.5 to 4.5 degrees C if carbon dioxide were to double and be held fixed over time.

Emissions scenarios, according to the IPCC, fall into six "equally sound" alternative paths. These paths span a doubling in carbon dioxide concentrations in 2100 up to more than tripling and well beyond tripling in the 22nd century. Lomborg, however, dismisses all but the lowest of the scenarios: "Temperatures will increase much less than the maximum estimates from IPCC—it is likely that the temperature will be at or below the B1 estimate [the lowest emissions scenario] (less than 2° C in 2100) and the temperature will certainly not increase even further into the twenty-second century."

Cost-benefit calculations show that although the benefits of avoiding climate change could be substantial ($5 trillion is the single figure Lomborg cites), this is not worth the cost to the economy of trying to constrain fossil-fuel emissions (a $3-trillion to $33-trillion range he pulls from the economics literature). Asymmetrically, no range is given for the climate damages.

The Kyoto Protocol, which caps industrialized countries' output of greenhouse gases, is too expensive. It would reduce warming in 2100 by only a few tenths of a degree—"putting off the temperature increase just six years." This number, though, is based on a strawman policy that nobody has seriously proposed: Lomborg extrapolates the Kyoto Protocol, which is applicable only up to 2012, as the world's sole climate policy for another nine decades.

Before providing specifics of why I believe each of these assertions is fatally

RICHARD HAMILTON SMITH *Corbis*

Lomborg admits, "I am not myself an expert as regards ENVIRONMENTAL PROBLEMS"—truer words are not found in the rest of the book.

flawed, I should say something about Lomborg's methods. First, most of his nearly 3,000 citations are to secondary literature and media articles. Moreover, even when cited, the peer-reviewed articles come elliptically from those studies that support his rosy view that only the low end of the uncertainty ranges will be plausible. IPCC authors, in contrast, were subjected to three rounds of review by hundreds of outside experts. They didn't have the luxury of reporting primarily from the part of the community that agrees with their individual views.

Second, it is ironic that in a popular book by a statistician one can't find a clear discussion of the distinction among different types of probabilities, such as frequentist and Bayesian (that is, "objective" and "subjective"). He uses the word "plausible" often, but, curiously for a statistician, he never attaches any probability to what is "plausible." The Third Assessment Report of the IPCC, on the other hand, explicitly confronted the need to quantify all confidence terms. Working Group I, for example, gave the term "likely" a 66 to 90 percent chance of occurring. Although the IPCC gives a wide range for most of its projections, Lomborg generally dismisses these ranges, focusing on the least serious outcomes. Not so much as one probability is offered for the chance of a dangerous outcome, yet he makes a firm assertion that climate "will certainly" not go beyond 2 degrees C warming in the 22nd century—a conclusion at variance with the IPCC, other national climate assessments and most recent studies in the field of climate science.

Now let us look in more detail at the four major arguments he makes in this chapter.

Climate science. A typical example of Lomborg's method is his paraphrase of a secondary source in reporting a 1989 Hadley Center paper in the journal *Nature* in which the researchers make modifications to their climate model: "The programmers then improved the cloud parameterizations in two places, and the model reacted by reducing its temperature estimate from 5.2° C to 1.9° C." Had this been first-rate scholarship, Lomborg would have consulted the original article, in which the concluding sentence of the first paragraph presents the authors' caveat: "Note that although the revised cloud scheme is more detailed it is not necessarily more accurate than the less sophisticated scheme."

In a similar vein, he cites Richard S. Lindzen's controversial stabilizing feedback, or "iris effect," as evidence that the IPCC climate sensitivity range should be reduced by a factor of almost three. He fails either to understand this mechanism or to tell us that it is based on only a few years of data in a small part of one ocean. Extrapolating this small sample of data to the entire globe is like extrapolating the strong destabilizing feedback over midcontinental landmasses as snow melts during the spring—such an inappropriate projection would likely increase estimates of climate sensitivity by a factor of several.

As a final example, he quotes a controversial hypothesis from Danish cloud physicists that solar magnetic events modulate cosmic rays and produce "a clear connection between global low-level cloud cover and incoming cosmic radiation." The Danish researchers use this hypothesis to support an alternative to carbon dioxide for explaining recent climate change. Lomborg fails to discuss—and I haven't seen it treated by the authors of that speculative theory either—what such purported changes to this cloud cover have done to the radiative balance of the earth. Increasing clouds, it has been well known since papers by Syukuro Manabe and Richard T. Wetherald in 1967 and myself in 1972, can warm or cool the atmosphere depending on the height of the cloud tops, the reflectivity of the underlying surface, the season and the latitude. The reason the IPCC discounts this theory is that its advocates have not demonstrated any radiative forcing sufficient to match that of much more parsimonious theories, such as anthropogenic forcing.

Emissions scenarios. Lomborg asserts that over the next several decades new, improved solar machines and other renewable technologies will crowd fossil fuels off the market. This will be done so efficiently that the IPCC scenarios vastly overestimate the chance for major increases in carbon dioxide. How I wish this would turn out to be true!

But wishes aren't analysis. One study is cited; ignored is the huge body of economics work he later accepts to estimate a range of costs if we were to implement emissions controls. In fact, most of these economists strongly believe high emissions are quite likely: they usually project carbon dioxide doubling to tripling (or more) as "optimal" economic policy. I have attacked this literature for failing to point out that climate policies that raise the price of conventional fuels spur investments in alternative energy systems. But such incentives need policies first—and Lomborg opposes those very policies. No credible analyst can just assert that a fossil-fuel-intensive scenario is not plausible—and, typically, he gives no probability that it might occur.

Cost-benefit calculations. Lomborg's most egregious distortions and poorest analyses are his citations of cost-benefit calculations. First, he chides the governments that modified the penultimate draft of the report from IPCC's Working Group II. These modifications downgraded the significance of economic studies that aggregate climate change damages. Lomborg says: "A political decision stopped IPCC from looking at the total cost-benefit of global warming." (As an aside, I should mention that it is strange he chose to cite the penultimate and *preapproval* draft report in this case but didn't mention the very first item in the *approved* summary—that recent temperature trends have caused a discernible effect on plants and animals. Even more puzzling is his failure to discuss ecological impacts in general, focusing instead on health and agriculture, sectors he thinks won't be much harmed by climate change of the minuscule amount he predicts.)

It is precisely because the responsible scientific community cannot rule out CATASTROPHIC OUTCOMES that climate mitigation policies are seriously proposed.

The government representatives downgraded aggregate cost-benefit studies for a reason: these studies fail to consider so many categories of damages held to be important by political leaders as to render them just a guideline on market-sector transactions, not the "total cost-benefit" analysis Lomborg wants. A total analysis would have to include the value of species lost, crucial ecosystem services degraded, inequity created by the poor being hurt more than the rich (which Lomborg does acknowledge), quality of life reduced (for example, a rise in sea level driving small-island inhabitants from traditional homelands), and likely changes to climatic extremes and variability. Then again, Lomborg cites only one value for climate damages—$5 trillion—even though the same economics papers he refers to for costs of climate policy generally acknowledge that climate damages can vary from benefits up to catastrophic losses.

It is precisely because the responsible scientific community cannot rule out such catastrophic outcomes at a high level of confidence that climate mitigation polices are seriously proposed. And to give one number—rather than a broad range—for avoided climate damages defies explanation, especially when he does give a range for climate policy costs. This range, however, is based on the economics literature but ignores the findings of engineers. Engineers dispute the economists' typical estimates because the economists fail to take into account preexisting market imperfections such as energy-inefficient machines, houses and processes. These engineering studies, including a famous one by five U.S. Department of Energy laboratories—hardly environmental radicals—suggest that climate policies that provide incentives to replace inefficient equipment with more efficient state-of-the-art products could actually reduce some emissions at *below-zero costs*.

The Kyoto Protocol. Lomborg's creation of a 100-year regime for a decade-long protocol is a distortion of the climate policy process. Every IPCC report has noted that carbon dioxide emissions need to be cut by more than 50 percent below most baseline projections to avoid large increases in concentration in the late 21st and 22nd centuries. Most analysts know "Kyoto extended" can't make such large cuts and that both developed and developing na-

JIM BRANDENBURG *Minden Pictures*

tions will have to fashion cooperative and cost-effective solutions over time. This will take a great deal of learning-by-doing: international cooperation is not a common experience. Kyoto is a starting point. And yet Lomborg, with his creation of a straw-man 100-year projection, would squash even this first step.

So what then is "the real state of the world"? Clearly, it isn't knowable in traditional statistical terms, even though subjective estimates can be responsibly offered. The ranges presented by the IPCC in its peer-reviewed reports give the best snapshot of the real state of climate change: we could be lucky and see a mild effect or unlucky and get the catastrophic outcomes. The IPCC frames the issue as a risk-management decision about hedging. It is not the everything-will-turn-out-fine affair that Lomborg would have us believe.

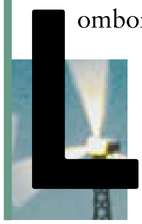
For such an interdisciplinary topic, the publisher would have been wise to ask natural scientists as well as social scientists to review the manuscript, which was published by the social science side of the house. It's not surprising that the reviewers failed to spot Lomborg's unbalanced presentation of the natural science, given the complexity of the many intertwining fields. But that the natural scientists weren't asked is a serious omission for a respectable publisher such as Cambridge University Press.

Unfortunately, angry reviews such as this one will be the result. Worse still, many laypeople and policymakers won't see the reviews and could well be tricked into thinking thousands of citations and hundreds of pages constitute balanced scholarship. A better rule of thumb is to see who talks in ranges and subjective probabilities and to beware of the myth busters and "truth tellers."

Stephen Schneider, professor in the department of biological sciences and senior fellow at the Institute for International Studies at Stanford University, is editor of Climatic Change *and the* Encyclopedia of Climate and Weather *and lead author of several IPCC chapters and the IPCC guidance paper on uncertainties.*

John P. Holdren

ENERGY: Asking the Wrong Question



Lomborg's chapter on energy covers a scant 19 pages. It is devoted almost entirely to attacking the belief that the world is running out of energy, a belief that Lomborg appears to regard as part of the "environmental litany" but that few if any environmentalists actually hold. What environmentalists mainly say on this topic is not that we are running out of energy but that we are running out of environment—that is, running out of the capacity of air, water, soil and biota to absorb, without intolerable consequences for human well-being, the effects of energy extraction, transport, transformation and use. They also argue that we are running out of the ability to manage other risks of energy supply, such as the political and economic dangers of overdependence on Middle East oil and the risk that nuclear energy systems will leak weapons materials and expertise into the hands of proliferation-prone nations or terrorists.

That "the energy problem" is not primarily a matter of depletion of resources in any global sense but rather of environmental impacts and sociopolitical risks—and, potentially, of rising monetary costs for energy when its environmental and sociopolitical hazards are adequately internalized and insured against—has in fact been the mainstream environmentalist position for decades. It was, for example, the position I elucidated in the 1971 Sierra Club "Battlebook" *Energy* (co-authored with Philip Herrera, then the environment editor for *Time*). It was also the position elaborated on by the Energy Policy Project of the Ford Foundation in the pioneering 1974 report *A Time to Choose;* by Amory Lovins in his influential 1976 *Foreign Affairs* article "Energy Strategy: The Road Not Taken"; by Paul R. and Anne H. Ehrlich and me in our 1977 college textbook *Ecoscience;* and so on.

So whom is Lomborg so resoundingly refuting with his treatise on the abundance of world energy resources? It would seem that his targets are pundits (such as the correspondents for *E* magazine and CNN cited at the opening of this chapter) and professional analysts (although only a few of these are cited, and those very selectively) who have argued not that the world is running out of energy altogether but only that it might be running out of cheap oil. Lomborg's dismissive rhetoric notwithstanding, this is not a silly question, nor one with an easy answer.

Oil is the most versatile and currently the most valuable of the conventional fossil fuels that have long provided the bulk of civilization's energy, and it remains today the largest contributor to world energy supply (accounting for nearly the whole of energy used for transport, besides other roles). But the recoverable conventional resources of oil are believed (on substantial evidence) to be far smaller than those of coal and probably also smaller than those of natural gas; the bulk of these resources appears to lie in the politically volatile Middle East; much of the rest lies offshore and in other difficult or environmentally fragile locations; and it is likely that the most abundant potential replacements for conventional oil will be more expensive than oil has been. For all these reasons, concerns about declining availability and rising prices have long been more salient for oil than for the other fossil fuels. There is, accordingly, a serious technical literature (produced mainly by geologists and economists) exploring the questions of when world oil production will peak and begin to decline and what the price of oil might be in 2010, 2030 or 2050, with considerable disagreement among informed professionals on the answers.

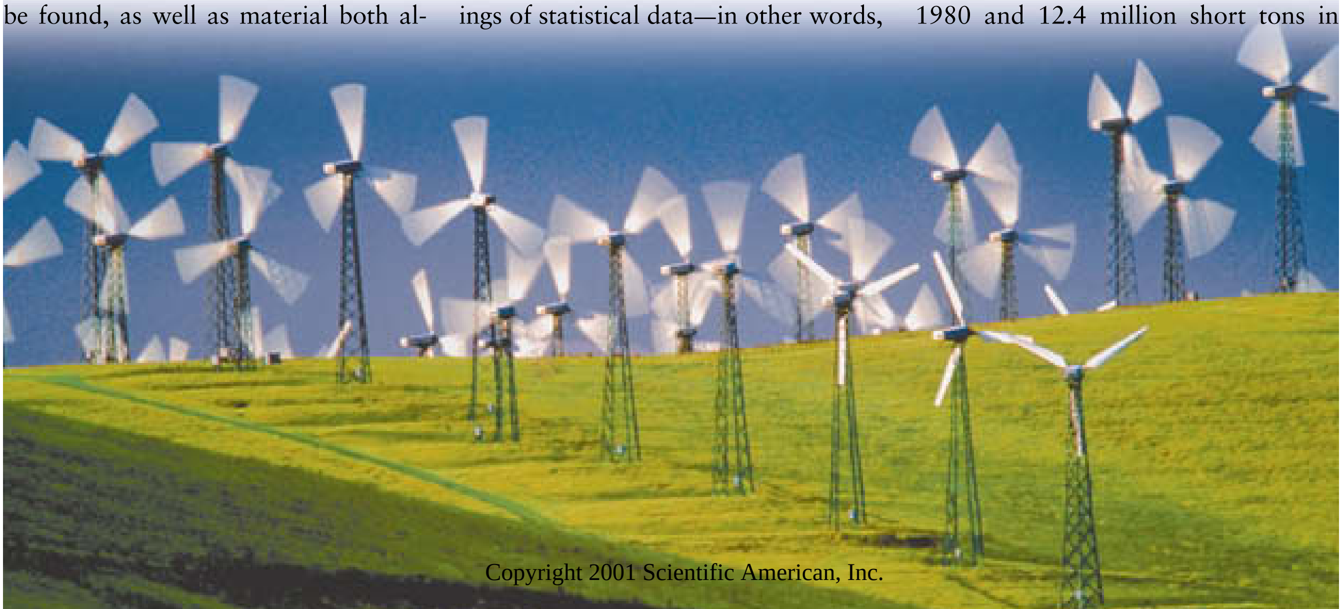
Lomborg gets right the basic point that the dominance of oil in the world energy market will end not because no oil is left in the ground but because other energy sources have become more attractive relative to oil. But he seems not to recognize that the transition from oil to other sources will not necessarily be smooth or occur at prices as low as those enjoyed by oil consumers today. Indeed, while ridiculing the position that the world's heavy oil dependence may again prove problematic in our lifetimes, he shows no sign of understanding (or no interest in communicating) why there is real debate among serious people about this.

What environmentalists mainly say on this topic is not that we are running out of energy but that we are RUNNING OUT OF ENVIRONMENT.

Lomborg does not so much as offer his readers a clear explanation of the distinction—crucial to understanding arguments about depletion—between "proved reserves" (referring to material that has already been found and is exploitable at a profit at today's prices, using today's technologies) and "remaining ultimately recoverable resources" (which incorporate estimates of additional material exploitable with today's technology at today's prices but still to be found, as well as material both already found and still to be found that will be exploitable with future technologies at potentially higher future prices). And, while noting that most of the world's oil reserves lie in the Middle East (and failing to note, having not even introduced the concept, that a still larger share of remaining ultimately recoverable resources is thought to lie there), he placidly informs us that it is "imperative for our future energy supply that this region remains reasonably peaceful," as if that observation did not undermine any basis for complacency. (At this juncture, one of his 2,930 footnotes helpfully adds that this peace imperative for the Middle East was "one of the background reasons for the Gulf War"!)

Lomborg's treatment of energy resources other than oil is not much better. He is correct in his basic proposition that resources of coal, oil shale, nuclear fuels and renewable energy are immense (which few environmentalists—and no well-informed ones—dispute). But his handling of the technical, economic and environmental factors that will govern the circumstances and quantities in which these resources might actually be used is superficial, muddled and often plain wrong. His mistakes include apparent misreadings or misunderstandings of statistical data—in other words, just the kinds of errors he claims are pervasive in the writings of environmentalists—as well as other elementary blunders of quantitative manipulation and presentation that no self-respecting statistician ought to commit.

He tells us correctly, for example, that the world has huge resources of coal, but in observing that "it is presumed that there is sufficient coal for well beyond the next 1,500 years" he says nothing about the rate of coal use for which this conclusion might obtain. Concerning the environmental questions that increased reliance on coal would raise, he writes the following: "Typically, coal pollutes quite a lot, but in developed economies switches to low-sulfur coal, scrubbers and other air-pollution control devices have today removed the vast part of sulfur dioxide and nitrogen dioxide emissions." To the contrary, data readily available on the Web in the Environmental Protection Agency report *National Air Pollutant Emission Trends 1900–1998* reveal that U.S. emissions of nitrogen oxides from coal-burning electric power plants were 6.1 million short tons in 1980 and 5.4 million short tons in 1998. Emissions of sulfur dioxide from U.S. coal-burning power plants were 16.1 million short tons in 1980 and 12.4 million short tons in



LESTER LEFKOWITZ *FPG International*

1998. These are moderate reductions, welcome but hardly the "vast part" of the emissions.

Concerning nuclear energy, Lomborg tells us that it "constitutes 6 percent of global energy production and 20 percent in the countries that have nuclear power." The first figure is right, the second seriously wrong. Nuclear energy provides a bit less than 10 percent of the primary energy supply in the countries that use this energy source. (It appears that Lomborg has confused contributions to the electricity sector with contributions to primary energy supply.) After a muddled discussion of the relation between uranium-resource estimates and breeding (which omits altogether the potentially decisive issue of the usability of uranium from seawater), he then barely notes in passing that breeder reactors "produce large amounts of plutonium that can be used for nuclear weapons production, thus adding to the security concerns." He should have added that this problem is so significant that it may preclude use of the breeding approach altogether, unless we develop technologies that make breeding much less susceptible to diversion of the plutonium while not making this approach even more uneconomic than it is today.

Lomborg has some generally sensible things to say about the large contributions that are possible from increased energy end-use efficiency and from renewable energy—on these topics he seems, to his credit, to be more a contributor to the "environmental litany" than a critic of it. But on these subjects as on the others, his treatment is superficial, uneven and marred by numerous errors and infelicities. For example, he persistently presents numbers to two- and three-figure precision for quantities that cannot be known to such accuracy: "43 percent of American energy use is wasted"; "the costs of carbon dioxide" emissions are "0.64 cents per kWh"; plant photosynthesis is "1,260 EJ" annually. He makes claims, based on single citations and without elaboration, that are far from representative of the literature: "We know today that it is possible to produce safe cars getting more than 50–100 km per liter (120–240 mpg)." (How big would these cars be, and powered how?) He bungles terminology: "Energy can be stored in hydrogen by catalyzing water." (He must mean "by electrolyzing water" or "by catalytic thermochemical decomposition of water.") And he propagates a variety of conceptual confusions, such as the idea that grid-connected wind power requires "a sizeable excess capacity" in the windmills because these alone "need to be able to meet peak demand."

Of course, much of what is most problematic in the global energy picture is covered by Lomborg not in his energy chapter but in those that deal with air pollution, acid rain, water pollution and global warming. The last is devastatingly critiqued by Stephen Schneider on page 62. There is no space to deal with the other energy-related chapters; suffice it to say that I found their level of superficiality, selectivity and misunderstanding roughly consistent with that of the energy chapter reviewed here. This is a shame. Lomborg is giving skepticism—and statisticians—a bad name.

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John Bongaarts

POPULATION: IGNORING ITS IMPACT

Around the world, countries are experiencing unprecedented demographic change. The best-known example is an enormous expansion in human numbers, but other important demographic trends also affect human welfare. People are living longer and healthier lives, women are bearing fewer children, increasing numbers of migrants are moving to cities and to other countries in search of a better life, and populations are aging. Lomborg's unbalanced presentation of some of these trends and their influences emphasizes the good news and neglects the bad. Environmentalists who predicted widespread famine and blamed rapid population growth for many of the world's environmental, economic and social problems overstated their cases. But Lomborg's view that "the number of people is not the problem" is simply wrong.

His selective use of statistics gives the reader the impression that the population problem is largely behind us. The global population growth rate has indeed declined slowly, but absolute growth remains close to the very high levels observed in recent decades, because the population base keeps expanding. World population today stands at six billion, three billion more than in 1960. According to U.N. projections, another three billion will likely be added by 2050, and population size will eventually reach about 10 billion.

Any discussion of global trends is misleading without taking account of the enormous contrasts among world regions. Today's poorest nations in Africa, Asia and Latin America have rapidly growing and young populations, whereas in the technologically advanced and richer nations in Europe, North America and Japan, growth is near zero (or, in some cases, even negative), and populations are aging quickly. As a consequence, nearly all future global growth will be concentrated in the developing countries, where four fifths of the world's population lives. The projected rise in population in the developing world between 2000 and 2025 (from 4.87 to 6.72 billion) is actually just as large as the record-breaking increase in the past quarter of a century. The historically unprecedented population expansion in the poorest parts of the world continues largely unabated.

The unprecedented POPULATION EXPANSION in the poorest parts of the world continues largely unabated.

Past population growth has led to high population densities in many countries. Lomborg dismisses concerns about this issue based on a simplistic and misleading calculation of density as the ratio of people to all land. Clearly, a more useful and accurate indicator of density would be based on the land that remains after excluding areas unsuited for human habitation or agriculture, such as deserts and inaccessible mountains. For example, according to his simple calculation, the population density of Egypt equals a manageable 68 persons per square kilometer, but if the unirrigated Egyptian deserts are excluded, density is an extraordinary 2,000 per square kilometer. It is therefore not surprising that Egypt needs to import a large proportion of its food supply. Measured properly, population densities have reached extremely high levels, particularly in large countries in Asia and the Middle East.

Why does this matter? The effect of population trends on human welfare has been debated for centuries. When the modern expansion of human numbers began in the late 18th century, Thomas Robert Malthus argued that population growth would be limited by food shortages. Lomborg and other technological optimists correctly note that world population has expanded much more rapidly than Malthus envisioned, growing from one billion to six billion over the past two centuries. And diets have improved. Moreover, the technological optimists are probably correct in claiming that overall world food production can be increased substantially over the next few decades. Average current crop yields are still below the levels achieved in the most productive countries, and some countries still have unused potential arable land (although much of this is forested).

Agricultural expansion, however, will be costly, especially if global food production has to rise twofold or even threefold to accommodate the demand for better diets from several billion more people. The land now used for agriculture is generally of better quality than unused, potentially cultivable land. Similarly, existing irrigation systems have been built on the most favorable sites. And water is increasingly in short supply in many countries as the competition for that resource among households, industry and agriculture intensifies. Consequently, each new increase in food production is becoming more expensive to obtain. This is especially true if one considers environmental costs not reflected in the price of agricultural products.

Lomborg's view that the production of more food is a nonissue rests heavily on the fact that world food prices are low and have declined over time. But this evidence is flawed. Massive governmental subsidies to farmers, particularly in the developed countries, keep food prices artificially low. Although technological developments have reduced prices, without these massive subsidies, world food prices would certainly be higher.

The environmental cost of what Paul R. and Anne H. Ehrlich describe as "turning the earth into a giant human feedlot" could be severe. A large expansion of agriculture to provide growing populations with improved diets is likely to lead to further deforestation, loss of species, soil erosion, and pollution

DIA MAX *FPG International*

from pesticides and fertilizer runoff as farming intensifies and new land is brought into production. Reducing this environmental impact is possible but costly and would obviously be easier if population growth were slower. Lomborg does not deny this environmental impact but asks unhelpfully, “What alternative do we have, with more than 6 billion people on Earth?”

Lomborg correctly notes that poverty is the main cause of hunger and malnutrition, but he neglects the contribution of population growth to poverty. This effect operates through two distinct mechanisms. First, rapid population growth leads to a young population, one in which as much as half is below the age of entry into the labor force. These young people have to be fed, housed, clothed and educated, but they are not productive, thus constraining the economy. Second, rapid population growth creates a huge demand for new jobs. A large number of applicants for a limited number of jobs exerts downward pressure on wages, contributing to poverty and inequality. Unemployment is widespread, and often workers in poor countries earn wages near the subsistence level. Both of these adverse economic effects are reversible by reducing birth rates. With lower birth rates, schools become less crowded, the ratio of dependents to workers declines as does the growth in the number of job seekers. These beneficial demographic effects contributed to the economic “miracles” of several East Asian countries. Of course, such dramatic results are by no means assured and can be realized only in countries with otherwise sound economic policies.

Lomborg approvingly notes the huge ongoing migration from villages to cities in the developing world. This has been considered a welcome development, because urban dwellers generally have higher standards of living than villagers. Because the flow of migrants is now so large, however, it tends to overwhelm the absorptive capacity of cities, and many migrants end up living in appalling conditions in slums. The traditional urban advantage is eroding in the poorest countries, and the health conditions in slums are often as adverse as in rural areas. This points to another burden of rapid population growth: the inability of governments to cope with large additions of new people. In many developing countries, investments in education, health services and infrastructure are not keeping up with population growth.

It is true that life has improved for many people in recent decades, but Lomborg does not acknowledge that this favorable trend has been brought about in part by intensive efforts by governments and the international community. Investments in developing and distributing “green revolution” technology have reduced hunger, public health campaigns have cut death rates, and family-planning programs have lowered birth rates. Despite this progress, some 800 million people are still malnourished, and 1.2 billion live in abject poverty. This very serious situation calls for more effective remedial action. Lomborg asks the developed nations to fulfill their U.N. pledge to donate 0.7 percent of their GNPs to assist the developing world, but few countries have met this goal, and the richest nation on earth, the U.S., is one of the stingiest, giving just 0.1 percent of its GNP. The trend in overseas development assistance from the developed to the developing world is down, not up. Unfortunately, the unrelenting we-are-doing-fine tone that pervades Lomborg’s book encourages complacency rather than urgency.

Population is not the main cause of the world’s social, economic and environmental problems, but it contributes substantially to many of them. If population had grown less rapidly in the past, we would be better off now. And if future growth can be slowed, future generations will be better off.

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Thomas Lovejoy

BIODIVERSITY: Dismissing Scientific Process

Biologists are trained to have a healthy respect for statistics and statisticians. It was disconcerting, therefore, to find that before even examining the extinction problem—and the numbers invoked to demonstrate that it is or is not a problem—Lomborg begins the chapter on biodiversity with a section questioning whether biodiversity is important. In less than a page, he discounts its value both as the library for the life sciences and as provider of ecosystem services (in part because of a general absence of markets for these services).

When he finally gets to extinction, he totally confounds the *process* by which a species is judged to be extinct with the estimates and projections of extinction *rates*. Highly conservative rules hold that to be declared officially extinct, not only does a species have to be known to science, it has to be observed going to extinction (as in the case of the passenger pigeon, the last individual of which perished in the Cincinnati Zoo in 1914). Or, in the absence of direct observation, it must not have been seen in nature for 50 years.

Projections of extinction rates, on the other hand, are generally based on the long-established relation between species number and area (which dates to 1921, not to the 1960s, as Lomborg

maintains, and which demonstrates the rate at which species number increases with increase in area). Researchers then project what the reduction in a natural habitat will mean in terms of species loss. The disappearance of a species is not necessarily instantaneous, and thus some species that survive the initial reduction of the habitat are essentially "living dead"—they are not able to survive over the long term. The loss of species from habitat remnants is a widely documented phenomenon—in contrast to Lomborg's inclusion of an out-of-date assertion that no credible attempt has been made to pin down the underlying scientific assumptions.

As a consequence, a seemingly major contradiction that Lomborg then offers is no contradiction at all: the reduction of the Brazilian Atlantic Forest formation to something on the order of 10 percent of its original extent and the lack of large numbers of recorded extinctions. First, this is a region with very few field biologists to record either species or their extinction. Second, there is abundant evidence that if the Atlantic forest remains as reduced and fragmented as it is, it will lose a sizable fraction of the species that at the moment are able to hang on.

In another supposed example of species surviving habitat loss, he notes that few species went extinct when the eastern forests of the U.S. were reduced to 1 to 2 percent of their original area. But only the old-growth forests shrank that much; total forest cover never fell below roughly 50 percent—allowing much biodiversity to survive as forest returned to an even greater area. Consequently, the small number of bird extinctions does not contradict what species-area considerations predict but instead confirms them.

In presenting an analysis for Puerto Rico, Lomborg again cites apparently contradictory evidence that although 99 percent of the primary forest was lost, the island ended up with more birds than it supported before deforestation. First of all, total forest cover was never so dramatically reduced. More significant, he ignores that seven of the 60 species unique to Puerto Rico were lost, and the additional species are not only invasives from other parts of the world but live in a wide variety of habitats. He completely misses the point that the world's bird fauna was reduced by seven species.

Lomborg takes particular exception to projections of massive extinction that started with Norman Myers's 1979 estimate that 40,000 species are being lost from the globe every year. There is some justification for this objection: Myers did not specify the method of arriving at his estimate. Nevertheless, he deserves credit for being the first to say that the number was large and for doing so at a time when it was difficult to make more accurate calculations. Current estimates are usually given in terms of the increases over normal extinction rates, which is preferable in that it is not necessary to assume a figure for the total number of species on the earth. That science does not know the total number of species does not prevent an estimation of extinction *rates*. Lomborg cynically dismisses the use of multiples of normal rates as being done because it sounds more "ominous" rather than recognizing the altered approach as an improvement in the science.

Estimates of present extinction rates range from 100 to 1,000 times normal, with most estimates at 1,000. The percent of bird (12), mammal (18), fish (5) and flowering plant (8) species threatened with extinction is consistent with that estimate. And the rates are certain to rise—and to do so exponentially—as natural habitats continue to dwindle.

The consideration of acid rain in a separate chapter is equally poorly researched and presented. Indeed, the research is so shallow that almost no citation from the peer-reviewed literature appears. Lomborg asserts that big-city pollution has nothing to do with acid rain, when it is fact that nitrogen compounds (NO_x) from traffic are a major source. His reference to a study showing that acid rain had no effect on the seedlings of three tree species neglects to mention that the study did not include conifer species such as red spruce, which *are* very sensitive. There is no acknowledgment of the delayed effects from acid rain leaching soil nutrients, particularly key cations. He confounds tree damage from air pollution 30 to 60 years ago with subsequent acid rain damage and makes an Alice-in-Wonderland statement that the only reason we worry about foliage loss is "because we have started monitoring this loss." It is simply untrue that "there is no case of forest decline in

Things improve *because* of the efforts of environmentalists to FLAG A PARTICULAR PROBLEM, investigate it and suggest policies to remedy it.

FRANS LANTING *Minden Pictures (above and opposite page)* which acidic deposition is known to be a predominant cause." Two clear-cut examples are red spruce in the Adirondacks and sugar maple in Pennsylvania.

The chapter on forests also suffers from superficial research and selective use of numbers. Lomborg starts by displaying Food and Agriculture Organization (FAO) data from 1948 to 2000. The FAO began by just reporting sums of "official data" furnished by governments (such data are notoriously uneven in quality and frequently overestimate forest stocks). Subsequently, the FAO adopted so many different definitions and methods that any statistician should know they could not be used for a valid time series.

Lomborg's discussion of the great fire in Indonesia in 1997 is still another instance of misleading readers with selective information. Yes, the WWF (World Wide Fund for Nature) first estimated the amount of forest burned at two million hectares, and Indonesia countered with official estimates of 165,000 to 219,000 hectares. But Lomborg fails to mention that the latter were not in the least credible and that in 1999 the Indonesian government and donor agencies, including the World Bank, signed off on a report that the real number was 4.6 million hectares.

From the very outset—his introductory chapter—Lomborg confuses forests and tree plantations. In criticizing a WWF estimate of loss of "natural wealth," he implies that the only value of forests is harvestable trees. That is analogous to valuing computer chips only for their silicon content. In fact, the metric the WWF used includes natural forests (because of their biodiversity) and omits plantations (because of their general lack thereof).

The central question of the book—Are things getting better?—is an important one. The reality is that significant progress has been made in abating acid rain, although much still needs to be done. And major efforts are under way to stem deforestation and to address the tsunami of extinction. But it is crucial to remember that whereas deforestation and acid rain are theoretically reversible (although there may be a threshold past which remedy is impossible), extinction is not. A dispassionate analysis, which Lomborg pretends to offer, of how far we have come and how far we have yet to go would have been a great contribution. Instead we see a pattern of denial.

The pattern is evident in the selective quoting. In trying to show that it is impossible to establish the extinction rate, he states: "Colinvaux admits in *Scientific American* that the rate is 'incalculable,'" when Paul A. Colinvaux's text, published in May 1989, is: "As human beings lay waste to massive tracts of vegetation, an incalculable and unprecedented number of species are rapidly becoming extinct." Why not show that Colinvaux thought the number is large? Biased language, such as "admits" in this instance, permeates the book.

In addition to errors of bias, the text is rife with careless mistakes. Time and again I sought to track references from the text to the footnotes to the bibliography to find but a mirage in the desert.

Far worse, Lomborg seems quite ignorant of how environmental science proceeds: researchers identify a potential problem, scientific examination tests the various hypotheses, understanding of the problem often becomes more complex, researchers suggest remedial policies—and *then* the situation improves. By choosing to highlight the initial step and skip to the outcome, he implies incorrectly that all environmentalists do is exaggerate. The point is that things improve *because* of the efforts of environmentalists to flag a particular problem, investigate it and suggest policies to remedy it. Sadly, the author seems not to reciprocate the respect biologists have for statisticians. SA

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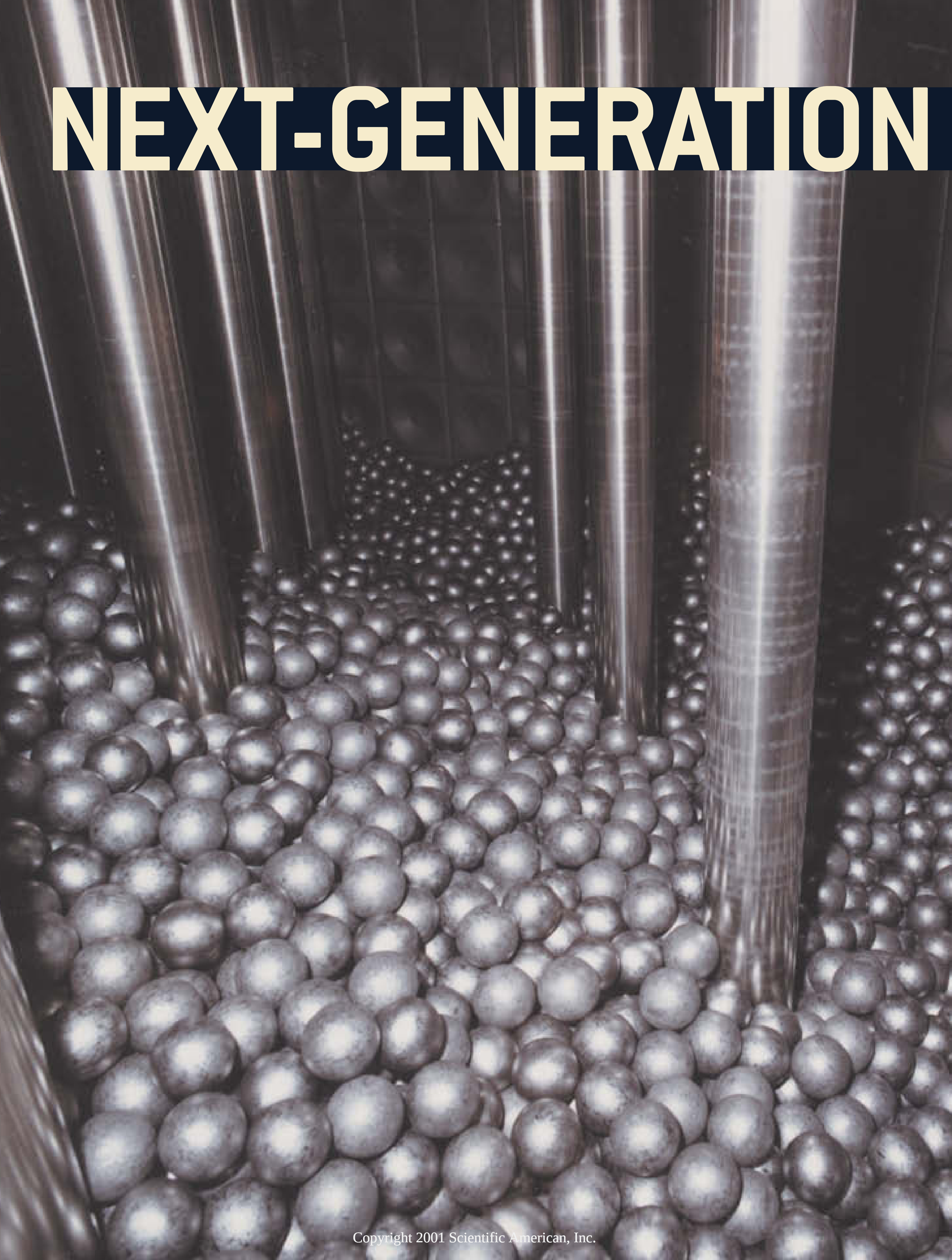
NEXT-GENERATION



NUCLEAR POWER

New, safer and more economical nuclear reactors could not only satisfy many of our future energy needs but could combat global warming as well

By James A. Lake, Ralph G. Bennett and John F. Kotek

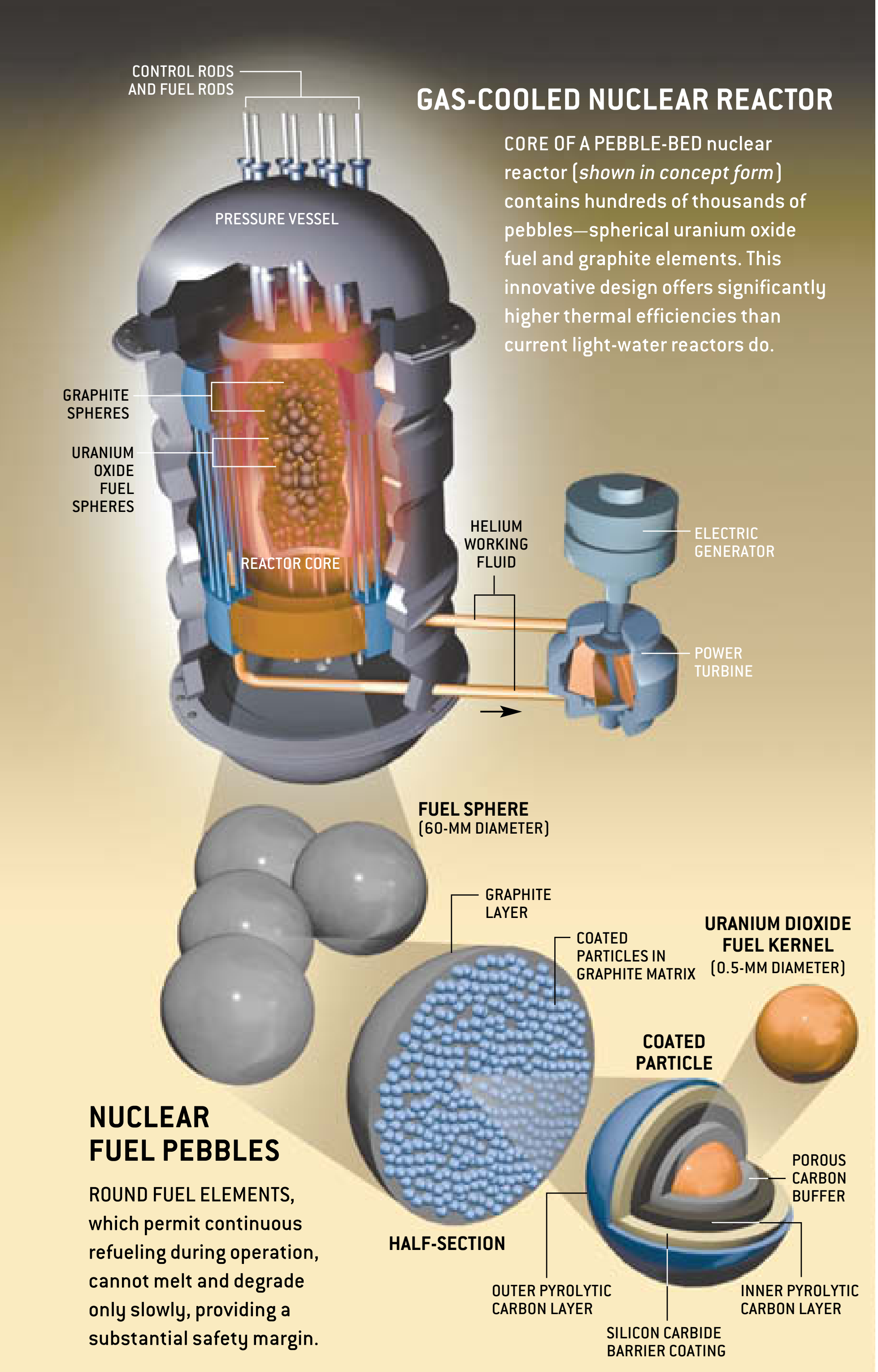
Rising electricity prices and last summer's rolling blackouts in California have focused fresh attention on nuclear power's key role in keeping America's lights on. Today 103 nuclear plants crank out a fifth of the nation's total electrical output. And despite residual public misgivings over Three Mile Island and Chernobyl, the industry has learned its lessons and established a solid safety record during the past decade. Meanwhile the efficiency and reliability of nuclear plants have climbed to record levels. Now with the ongoing debate about reducing greenhouse gases to avoid the potential onset of global warming, more people are recognizing that nuclear reactors produce electricity without discharging into the air carbon dioxide or pollutants such as nitrogen oxides and smog-causing sulfur compounds. The world demand for energy is projected to rise by about 50 percent by 2030 and to nearly double by 2050. Clearly, the time seems right to reconsider the future of nuclear power [see "The Case for Nuclear Power," on page 76].

No new nuclear plant has been ordered in the U.S. since 1978, nor has a plant been finished since 1995. Resumption of large-scale nuclear plant construction requires that challenging questions be addressed regarding the achievement of economic viability, improved operating safety, efficient waste management and resource utilization, as well as weapons nonproliferation, all of which are influenced by the design of the nuclear reactor system that is chosen.

Designers of new nuclear systems are adopting novel approaches in the attempt to attain success. First, they are embracing a system-wide view of the nuclear fuel cycle that encompasses all steps from the mining of ore through the management of wastes and the development of the infrastructure to support these steps. Second, they are evaluating systems in terms of their sustainability—meeting present needs without jeopardizing the ability of future generations to prosper. It is a strategy that helps to illuminate the relation between energy supplies and the needs of the environment and society. This emphasis on sustainability can lead to the development of nuclear energy–derived products besides electrical power, such as hydrogen fuel for transportation. It also promotes the exploration of alternative reactor designs and nuclear fuel–recycling processes that could yield significant reductions in waste while recovering more of the energy contained in uranium.

We believe that wide-scale deployment of nuclear power technology offers

PEBBLE PILE: Billiard-ball-size nodules of coated uranium fuel and graphite as well as control rods constitute the core of an experimental gas-cooled nuclear reactor in Germany.



GAS-COOLED NUCLEAR REACTOR

CORE OF A PEBBLE-BED nuclear reactor (*shown in concept form*) contains hundreds of thousands of pebbles—spherical uranium oxide fuel and graphite elements. This innovative design offers significantly higher thermal efficiencies than current light-water reactors do.

NUCLEAR FUEL PEBBLES

ROUND FUEL ELEMENTS, which permit continuous refueling during operation, cannot melt and degrade only slowly, providing a substantial safety margin.

COURTESY OF NUCLEAR ENGINEERING INTERNATIONAL (*preceding pages*); DON FOLEY (*this page*)

substantial advantages over other energy sources yet faces significant challenges regarding the best way to make it fit into the future.

Future Nuclear Systems

IN RESPONSE to the difficulties in achieving sustainability, a sufficiently high degree of safety and a competitive economic basis for nuclear power, the U.S. Department of Energy initiated the Generation IV program in 1999. Generation IV refers to the broad division of nuclear designs into four categories: early prototype reactors (Generation I), the large central station nuclear power plants of today (Generation II), the advanced lightwater reactors and other systems with inherent safety features that have been designed in recent years (Generation III), and the next-generation systems to be designed and built two decades from now (Generation IV) [*see box on opposite page*]. By 2000 international interest in the Generation IV project had resulted in a nine-country coalition that includes Argentina, Brazil, Canada, France, Japan, South Africa, South Korea, the U.K. and the U.S. Participating states are mapping out and collaborating on the research and development of future nuclear energy systems.

Although the Generation IV program is exploring a wide variety of new systems, a few examples serve to illustrate the broad approaches reactor designers are developing to meet their objectives. These next-generation systems are based on three general classes of reactors: gas-cooled, water-cooled and fast-spectrum.

Gas-Cooled Reactors

NUCLEAR REACTORS using gas (usually helium or carbon dioxide) as a core coolant have been built and operated successfully but have achieved only limited use to date. An especially exciting prospect known as the pebble-bed modular reactor possesses many design features that go a good way toward meeting Generation IV goals. This gas-cooled system is being pursued by engineering teams in China, South Africa and the U.S. South Africa plans to build a full-size prototype and begin operation in 2006.

The pebble-bed reactor design is based on a fundamental fuel element, called a pebble, that is a billiard-ball-size graphite sphere containing about 15,000 uranium oxide particles with the diameter of poppy seeds [*see illustration at left*]. The evenly dispersed particles each have several high-density coatings on them. One of the layers, composed of tough silicon carbide ceramic, serves as a pressure vessel to retain the products of nuclear fission during reactor operation or accidental temperature excursions. About 330,000 of these spherical fuel pebbles are placed into a metal vessel surrounded by a shield of graphite blocks. In addition, as many as 100,000 unfueled graphite pebbles are loaded into the core to shape its power and temperature distribution by spacing out the hot fuel pebbles.

NUCLEAR POWER PRIMER

MOST OF THE WORLD'S nuclear power plants are pressurized water reactors. In these systems, water placed under high pressure (155 atmospheres) to suppress boiling serves as both the coolant and the working fluid. Initially developed in the U.S. based on experience gained from the American naval reactor program, the first commercial pressurized light-water reactor commenced operation in 1957.

The reactor core of a pressurized water reactor is made up of arrays of zirconium alloy–clad fuel rods composed of small cylinders (pellets) of mildly enriched uranium oxide with the diameter of a dime. A typical 17-by-17-square array of fuel rods constitutes a fuel assembly, and about 200 fuel assemblies are arranged to form a reactor core. Cores, which are typically approximately 3.5 meters in diameter and 3.5 meters high, are contained within steel pressure vessels that are 15 to 20 centimeters thick.

The nuclear fission reactions produce heat that is removed by circulating water. The coolant is pumped into the core at about 290 degrees Celsius and exits the core at about 325 degrees C. To control the power level, control rods are inserted into the fuel arrays. Control rods are made of materials that moderate the fission reaction by absorbing the slow (thermal) neutrons emitted during fission. They are raised out of or lowered into the core to control the rate of the nuclear reaction. To change the fuel or in the case of an accident, the rods are lowered all the way into the core to shut down the reaction.

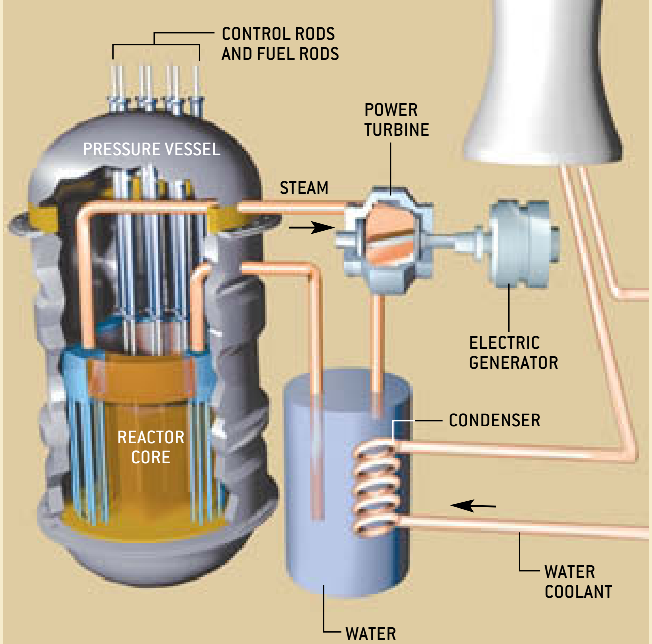
In the primary reactor coolant loop, the hot water exits the reactor core and flows through a heat exchanger (called a steam generator), where it gives up its heat to a secondary steam loop that operates at a lower pressure level. The steam produced in the heat exchanger is then expanded through a steam turbine, which in turn spins a generator to produce electricity (typically 900 to 1,100 megawatts). The steam is then condensed and pumped back into the heat exchanger to complete the loop. Aside from the source of heat, nuclear power plants are generally similar to coal- or fuel-fired electrical generating facilities.

There are several variants of the light-water-cooled reactor, most notably boiling-water reactors, which operate at lower pressure (usually 70 atmospheres) and generate steam directly in the reactor core, thus eliminating the need for the intermediate heat exchanger. In a smaller number of nuclear power plants, the reactor coolant fluid is heavy water (containing the hydrogen isotope deuterium), carbon dioxide gas or a liquid metal such as sodium.

The reactor pressure vessel is commonly housed inside a concrete citadel that acts as a radiation shield. The citadel is in turn enclosed within a steel-reinforced concrete containment building. The containment building is designed to prevent leakage of radioactive gases or fluids in an accident.

—J.A.L., R.G.B. and J.F.K.

PRESSURIZED LIGHT-WATER NUCLEAR POWER PLANT



DON FOLEY

Heat-resistant refractory materials are used throughout the core to allow the pebble-bed system to operate much hotter than the 300 degree Celsius temperatures typically produced in today's light-water-cooled (Generation II) designs. The helium working fluid, exiting the core at 900 degrees C, is fed directly into a gas turbine/generator system that generates electricity at a comparatively high 40 percent thermal efficiency level, one quarter better than current light-water reactors.

The comparatively small size and the general simplicity of pebble-bed reactor designs add to their economic feasibility. Each power module, producing 120 megawatts of electrical output, can be deployed in a unit one tenth the size of today's central station plants, which permits the development of more flexible, modest-scale projects that may offer more favorable economic results. For example, modular systems can be manufactured in the factory and then shipped to the construction site.

The pebble-bed system's relative simplicity compared with current designs is dramatic: these units have only about two dozen major plant subsystems, compared with about 200 in light-water reactors. Significantly, the operation of these plants can be extend-

THE CASE FOR NUCLEAR POWER

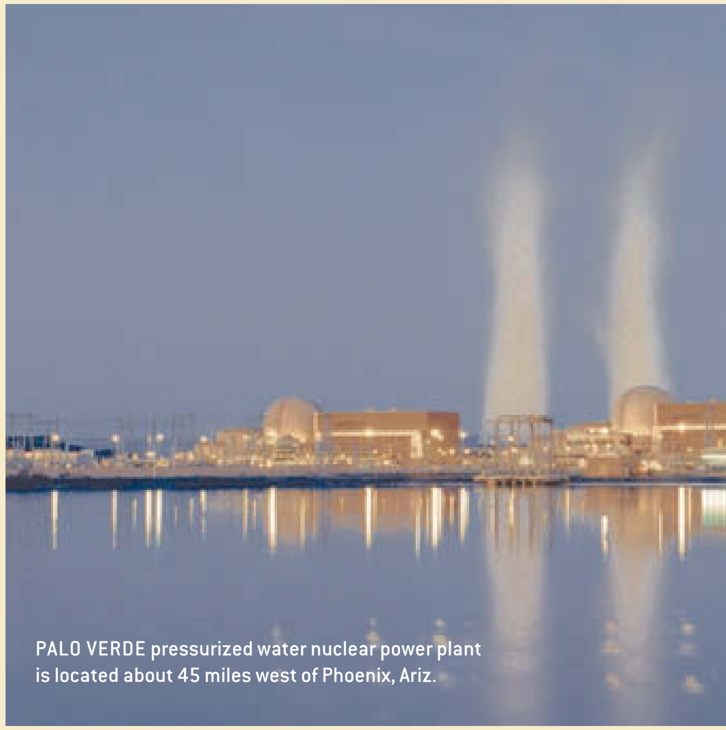
TODAY 438 NUCLEAR POWER PLANTS generate about 16 percent of the world's electricity. In the U.S., 103 nuclear power plants provide about 20 percent of the country's electrical production. Although no new nuclear facilities have been ordered in the U.S. for more than two decades, the electrical output of U.S. generators has grown by almost 8 percent a year as the industry matured and became more efficient. In the past 10 years alone, American nuclear plants have added more than 23,000 megawatts—the equivalent of 23 large power plants—to the total electricity supply despite the lack of any new construction. In the meantime, the production increase has lowered the unit cost of nuclear power generation. This improvement has led to growing interest among the business community in extending plant operating licenses and perhaps purchasing new nuclear facilities.

It may be surprising to some that the use of nuclear energy has direct benefits to the environment, specifically air quality. Although debate continues about the potential for the disruption of the earth's climate by emissions of carbon dioxide and other greenhouse gases, there is no doubt about the serious health consequences of air pollution from the burning of fossil fuels. Unlike fossil-fuel power plants, nuclear plants do not produce carbon dioxide, sulfur or nitrogen oxides. Nuclear power production in the U.S. annually avoids the emission of more than 175 million tons of carbon that would have been released into the environment if the same amount of electricity had instead been generated by burning coal.

Little attention has been paid to nuclear energy's capacity for producing hydrogen for use in transportation fuel cells and other cleaner power plants. A very straightforward approach is to use the energy from a high-temperature nuclear reactor to drive a steam-reforming reaction of methane. This process still creates carbon dioxide as a by-product, however. Several direct thermochemical reactions can give rise to hydrogen using water and high temperature. Research on the thermochemical decomposition of sulfuric acid and other hydrogen-forming reactions is under way in Japan and the U.S. The economics of nuclear-based hydrogen remain to be proved, but enormous potential exists for this route, perhaps operating in a new electricity-hydrogen cogeneration mode.

Improving Economics

Any nuclear construction in the U.S. must address challenging economic issues concerning their capital costs and financing. The problem is that the current generation of nuclear power plants, represented by three Nuclear Regulatory Commission–certified advanced light-water reactor designs, costs about $1,500 per kilowatt electric (kWe) of generating capacity, which may not be sufficiently competitive to restart nuclear construction. A widely discussed cost goal for new (Generation III and IV) nuclear plant projects is $1,000 per kWe. Achievement of this aim would make them competitive (on a unit-cost basis) with the most economical alternative, the combined-cycle natural gas plant. Any next-generation facilities must in addition be completed within about three



PALO VERDE pressurized water nuclear power plant is located about 45 miles west of Phoenix, Ariz.

years to keep financing costs to a manageable level. New streamlined, but as yet untried, licensing procedures should speed the process.

Given the past experience with nuclear projects in the U.S., it will be difficult for designers and builders to meet these goals. To achieve the cost objective, nuclear engineers are seeking to attain higher thermal efficiencies by raising operating temperatures and simplifying subsystems and components. Speeding plant construction will require the standardization of plant designs, factory fabrication and certification procedures; the division of plants into smaller modules that avoid the need for on-site construction; and the use of computerized assembly-management techniques. In this way, the building work can be verified in virtual reality before it proceeds in the field.

Advancing Safety

As the economic performance of the nuclear power industry has improved over the past 20 years, so too has its safety performance. The Three Mile Island accident in 1979 focused the attention of plant owners and operators on the need to boost safety margins and performance. The number of so-called safety-significant events reported to the Nuclear Regulatory Commission, for example, averaged about two per plant per year in 1990 but had dropped to less than one tenth of that by 2000. In the meantime, public confidence in the safety of nuclear power has been largely restored since the Chernobyl accident in 1986, according to recent polls.

Long-term safety goals for next-generation nuclear facilities were formulated during the past year by international and domestic experts at the request of the U.S. Department of Energy. They

established three major objectives: to improve the safety and reliability of plants, to lessen the possibility of significant damage during accidents, and to minimize the potential consequences of any accidents that do occur. Accomplishing these aims will require new plant designs that incorporate inherent safety features to prevent accidents and to keep accidents from deteriorating into more severe situations that could release radioactivity into the environment.

Nuclear Waste Disposal and Reuse

Outstanding issues regarding the handling and disposal of nuclear waste and safeguarding against nuclear proliferation must also be addressed. The Yucca Mountain long-term underground repository in Nevada is being evaluated to decide whether it can successfully accept spent commercial fuel. It is, however, a decade behind schedule and even when completed will not accommodate the quantities of waste projected for the future.

The current "once-through," or open, nuclear fuel cycle uses freshly mined uranium, burns it a single time in a reactor and then discharges it as waste. This approach results in only about 1 percent of the energy content of the uranium being converted to electricity. It also produces large volumes of spent nuclear fuel that must be disposed of in a safe fashion. Both these drawbacks can be avoided by recycling the spent fuel—that is, recovering the useful materials from it.

Most other countries with large nuclear power programs—including France, Japan and the U.K.—employ what is called a closed nuclear fuel cycle. In these countries, used fuel is recycled to recover uranium and plutonium (produced during irradiation in reactors) and reprocess it into new fuel. This effort doubles the amount of energy recovered from the fuel and removes most of the long-lived radioactive elements from the waste that must be permanently stored. It should be noted, though, that recycled fuel is today more expensive than newly mined fuel. Current recycling technology also leads to the separation of plutonium, which could potentially be diverted into weapons.

Essentially all nuclear fuel recycling is performed using a process known as PUREX (plutonium uranium extraction), which was initially developed for extracting pure plutonium for nuclear weapons. In PUREX recycling, used fuel assemblies are transported to a recycling plant in heavily shielded, damage-resistant shipping casks. The fuel assemblies are chopped up and dissolved by strong acids. The fuel solution then undergoes a solvent-extraction procedure to separate the fission products and other elements from the uranium and the plutonium, which are purified. The uranium and plutonium are used to fabricate mixed oxide fuel for use in light-water reactors.

Recycling helps to minimize the production of nuclear waste. To reduce the demand for storage space, a sustainable nuclear fuel cycle would separate the short-lived, high-heat-producing fission products, particularly cesium 137 and strontium 90. These elements would be held separately in convectively cooled facilities for 300 to 500 years, until they had decayed to safe levels. An optimized closed (fast-reactor) fuel cycle would recycle not just the uranium and plutonium but all actinides in the fuel, including neptunium, americium and curium. In a once-through fuel cycle, more than 98 percent of the expected long-term radiotoxicity is caused by the resulting neptunium 237 and plutonium 242 (with half-lives of 2.14 million and 387,000 years, respectively). Controlling the long-term effects of a repository becomes simpler if these long-lived actinides are also separated from the waste and recycled. The removal of cesium, strontium and the actinides from the waste shipped to a geological repository could increase its capacity by a factor of 50.

Because of continuing interest in advancing the sustainability and economics of nuclear fuel cycles, several countries are developing more effective recycling technologies. Today an electrometallurgical process that precludes the separation of pure plutonium is under development in the U.S. at Argonne National Laboratory. Advanced aqueous recycling procedures that offer similar advantages are being studied in France, Japan and elsewhere.

Ensuring Nonproliferation

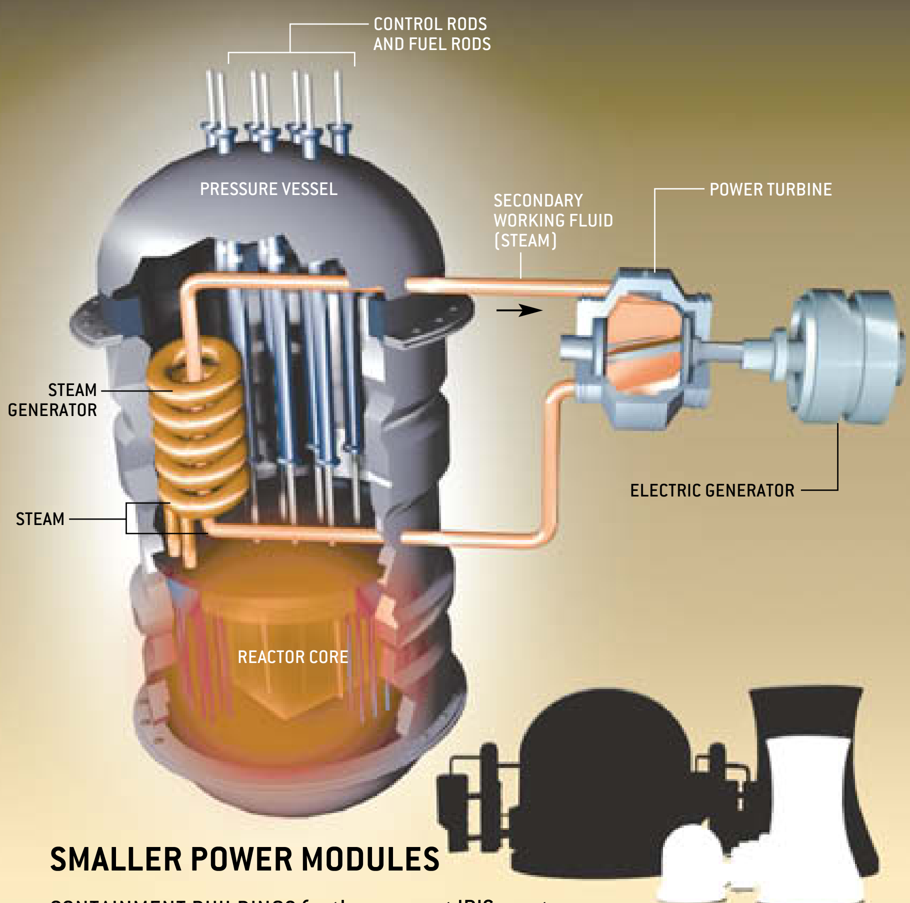
A critical aspect of new nuclear energy systems is ensuring that they do not allow weapons-usable materials to be diverted from the reprocessing cycle. When nations acquire nuclear weapons, they usually develop dedicated facilities to produce fissile materials rather than collecting nuclear materials from civilian power plants. Commercial nuclear fuel cycles are generally the most costly and difficult route for production of weapons-grade materials. New fuel cycles must continue to be designed to guard against proliferation.

—J.A.L., R.G.B. and J.F.K.

ARIZONA PUBLIC SERVICE

WATER-COOLED NUCLEAR REACTOR

IRIS REACTOR DESIGN developed by Westinghouse Electric (*depicted in conceptual form*) is novel in that both the steam generator (heat exchanger) and the control rod actuator drives are enclosed within the thick steel pressure vessel.



SMALLER POWER MODULES

CONTAINMENT BUILDINGS for the compact IRIS reactor can be reduced in size. The reactor's lower power output, ranging from 100 to 350 megawatts, can make these units more economical as well.

ed into a temperature range that makes possible the low emissions production of hydrogen from water or other feedstocks for use in fuel cells and clean-burning transportation engines, technologies on which a sustainable hydrogen-based energy economy could be based [*see box on page 76*].

These next-generation reactors incorporate several important safety features as well. Being a noble gas, the helium coolant will not react with other materials, even at high temperatures. Further, because the fuel elements and reactor core are made of refractory materials, they cannot melt and will degrade only at the extremely high temperatures encountered in accidents (more than 1,600 degrees C), a characteristic that affords a considerable margin of operating safety.

Yet other safety benefits accrue from the continuous, on-line fashion in which the core is refueled: during operation, one pebble is removed from the bottom of the core about once a minute as a replacement is placed on top. In this way, all the pebbles gradually move down through the core like gumballs in a dispensing machine, taking about six months to do so. This feature means that the system contains the optimum amount of fuel for operation, with little extra fissile reactivity. It eliminates an entire class of excess-reactivity accidents that can occur in current water-cooled reactors. Also, the steady movement of pebbles through regions of high and low power production means that each experiences less extreme operating conditions on average than do fixed fuel configurations, again adding to the unit's safety margin. After use, the spent pebbles must be placed in long-term storage repositories, the same way that used-up fuel rods are handled today.

Water-Cooled Reactors

EVEN STANDARD water-cooled nuclear reactor technology has a new look for the future. Aiming to overcome the possibility of accidents resulting from loss of coolant (which occurred at Three Mile Island) and to simplify the overall plant, a novel class of Generation IV systems has arisen in which all the primary components are contained in a single vessel. An American design in this class is the international reactor innovative and secure (IRIS) concept developed by Westinghouse Electric.

Housing the entire coolant system inside a damage-resistant pressure vessel means that the primary system cannot suffer a major loss of coolant even if one of its large pipes breaks. Because the pressure vessel will not allow fluids to escape, any resulting accident is limited to a much more moderate drop in pressure than could occur in previous designs.

To accomplish this compact configu-

THE AUTHORS

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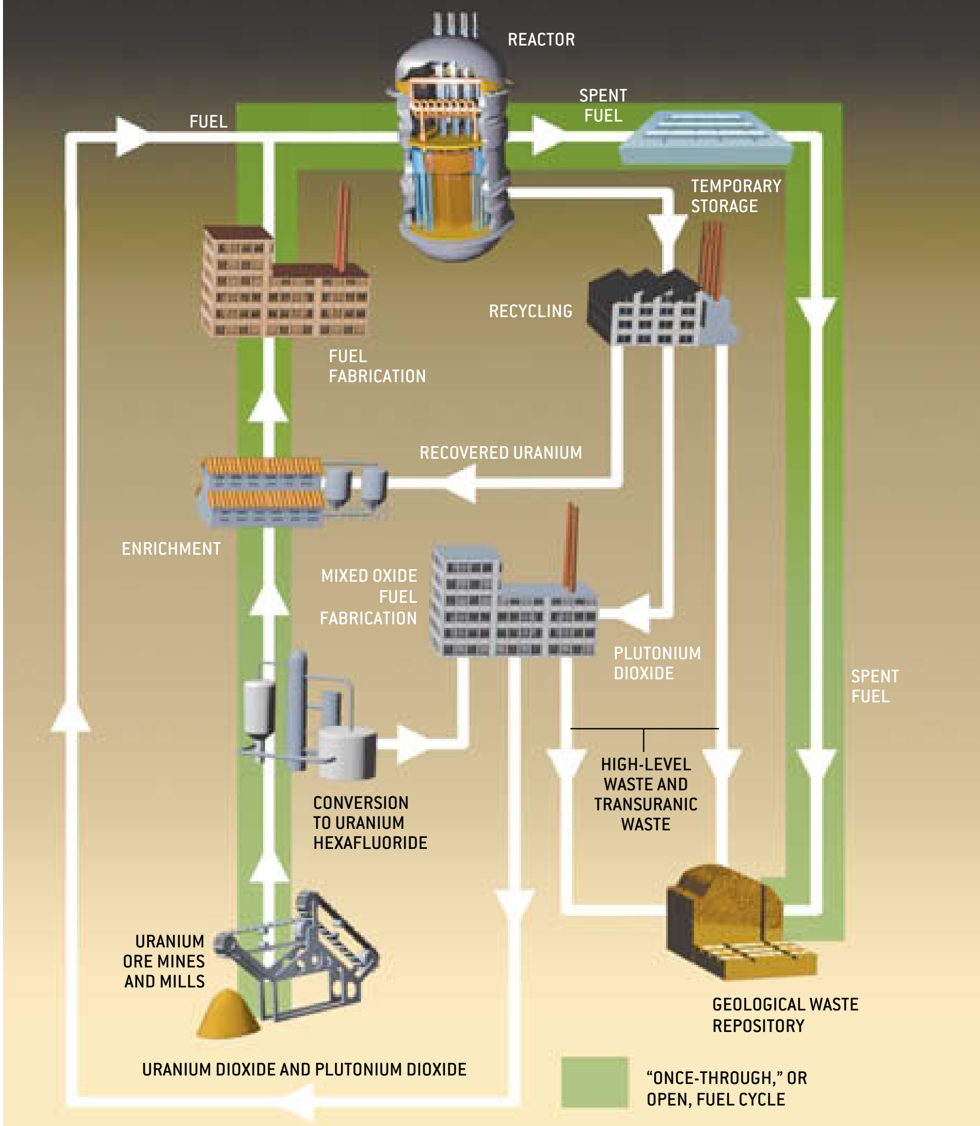
DON FOLEY

OPEN AND CLOSED NUCLEAR FUEL CYCLES

"ONCE-THROUGH," or open, nuclear fuel cycle (*shown in green*) takes uranium ore, processes it into fissile fuel, burns it a single time in a reactor and then disposes of it in a geological repository. This approach, which is employed the U.S., uses only 1 percent of the uranium's energy content. In a closed cycle (*shown in white*), the spent fuel is processed to reclaim its uranium and plutonium fuel content for reuse. This recycling method is used today in France, Japan and the U.K. Future closed cycles based on fast-spectrum reactors could reclaim other actinides that are currently treated as waste.



DON FOLEY

ration, several important simplifications are incorporated in these reactors. The subsystems within the vessel are stacked to enable passive heat transfer by natural circulation during accidents. In addition, the control rod drives are located in the vessel, eliminating the chance that they could be ejected from the core. These units can also be built as small power modules, thereby allowing more flexible and lower-cost deployment.

Designers of these reactors are also exploring the potential of operating plants at high temperature and pressure (more than 374 degrees C and 221 atmospheres), a condition known as the critical point of water, at which the distinction between liquid and vapor blurs. Beyond its critical point, water behaves as a continuous fluid with exceptional specific heat (thermal storage capacity) and superior heat transfer (thermal conductance) properties. It also does not boil as it heats up or flash to steam if it undergoes rapid depressurization. The primary advantage to operating above the critical point is that the system's thermal efficiency can reach as high as 45 percent and approach the elevated temperature regime at which hydrogen fuel production can become viable.

Although reactors based on supercritical water appear very similar to standard Generation II designs at first glance, the differences are many. For instance, the cores of the former are considerably smaller, which helps to economize on the pressure vessel and the surrounding plant. Next, the associated steam-cycle equipment is substantially simplified because it operates with a single-phase working fluid. In addition, the smaller core and the low coolant density reduce the volume of water that must be held within the containment vessel in the event of an accident. Because the low-density coolant does not moderate the energy of the neutrons, fast-spectrum reactor designs, with their associated sustainability benefits, can be contemplated. The chief downside to supercritical water systems is that the coolant becomes increasingly corrosive. This means that new materials and methods to control corrosion and erosion must be developed. Supercritical water reactor research is ongoing in Canada, France, Japan, South Korea and the U.S.

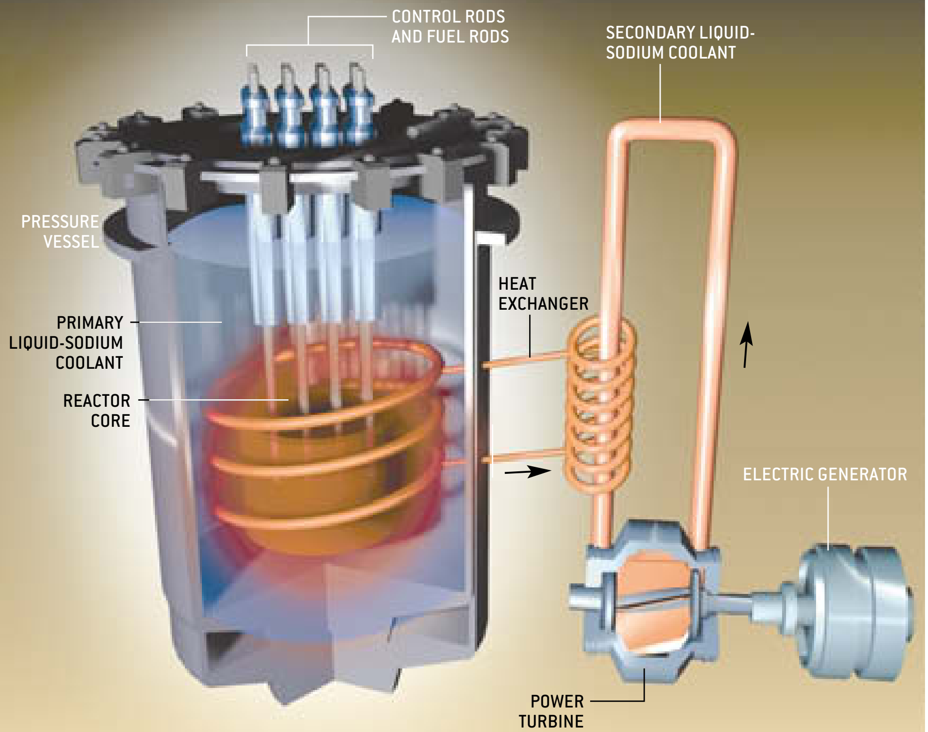
Fast-Spectrum Reactors

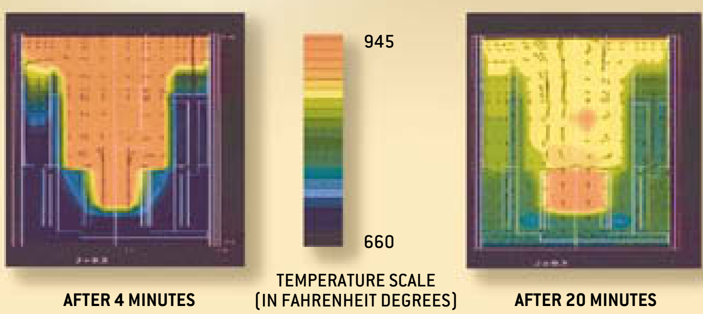
A DESIGN APPROACH for the longer term is the fast-spectrum (or high-energy neutron) reactor, another type of Generation IV system. An example of this class of reactor is being pursued by design teams in France, Japan, Russia, South Korea and elsewhere. The American fast-reactor development program was canceled in 1995, but U.S. interest might be revived under the Generation IV initiative.

Most nuclear reactors employ a thermal, or relatively low energy, neutron-emissions spectrum. In a thermal reactor the fast (high-energy) neutrons generated

FAST-SPECTRUM NUCLEAR REACTOR

CORES OF FAST-SPECTRUM nuclear reactors such as General Electric's Super PRISM design (*shown in conceptual form*), which produce fast (high-energy) neutrons, are often cooled with molten metals. In breeder-reactor configurations, these high-energy neutrons are used to create nuclear fuel.





PASSIVE CORE COOLING

TEMPERATURE DISTRIBUTIONS show how the high heat-transfer properties of liquid-metal coolants can lower the reactor core temperature passively following the accidental loss of the external heat sink.

DON FOLEY

in the fission reaction are slowed down to "thermal" energy levels as they collide with the hydrogen in water or other light nuclides. Although these reactors are economical for generating electricity, they are not very effective in producing nuclear fuel (in breeder reactors) or recycling it.

Most fast-spectrum reactors built to date have used liquid sodium as the coolant. Future versions of this reactor class may utilize sodium, lead, a lead-bismuth alloy or inert gases such as helium or carbon dioxide. The higher-energy neutrons in a fast reactor can be used to make new fuel or to destroy long-lived wastes from thermal reactors and plutonium from dismantled weapons. By recycling the fuel from fast reactors, they can deliver much more energy from uranium while reducing the amount of waste that must be disposed of for the long term. These breeder-reactor designs are one of the keys to increasing the sustainability of future nuclear energy systems, especially if the use of nuclear energy is to grow significantly.

Beyond supporting the use of a fast-neutron spectrum, metal coolants have several attractive qualities. First, they possess exceptional heat-transfer properties, which allows metal-cooled reactors to withstand accidents like the ones that happened at Three Mile Island and Chernobyl. Second, some (but not all) liquid metals are considerably less corrosive to components than water is, thereby extending the operating life of reactor vessels and other critical subsystems. Third, these high-temperature systems can operate near atmospheric pressure, greatly simplifying system design and reducing potential industrial hazards in the plant.

More than a dozen sodium-cooled reactors have been operated around the world. This experience has called attention to two principal difficulties that must be overcome. Sodium reacts with water to generate high heat, a possible accident source. This characteristic has led sodium-cooled reactor designers to include a secondary sodium system to isolate the primary coolant in the reactor core from the water in the electricity-producing steam system. Some new designs focus on novel heat-exchanger technologies that guard against leaks.

The second challenge concerns economics. Because sodium-cooled reactors require two heat-transfer steps between the core and the turbine, capital costs are increased and thermal efficiencies are lower than those of the most advanced gas- and water-cooled concepts (about 38 percent in an advanced sodium-cooled reactor compared with 45 percent in a supercritical water reactor). Moreover, liquid metals are opaque, making inspection and maintenance of components more difficult.

Next-generation fast-spectrum reactor designs attempt to capitalize on the advantages of earlier configurations while addressing their shortcomings. The technology has advanced to the point at

HOW SECURE ARE NUCLEAR PLANTS FROM TERRORISTS?

THE TRAGIC EVENTS of September 11, 2001, raise troubling questions about the vulnerability of nuclear facilities to terrorist attacks. Although stringent civilian and military security countermeasures have been implemented to stop determined assaults, the deliberate crash of a large commercial airliner looms in the imagination. So, should Americans be worried? The answer is no and yes.

A nuclear power plant is not an easy target for an airliner flying at high speed, because an off-center hit on a domed, cylindrical containment building would not substantially affect the building structure. Located at or below grade, the reactor core itself is typically less than 10 feet in diameter and 12 feet high. It is enclosed in a heavy steel vessel surrounded by a concrete citadel. Reactor containment designs differ in their details, but in all cases they are meant to survive the worst of nature's forces (including earthquakes, tornadoes and hurricanes). Despite not being designed to resist acts of war, containment enclosures can withstand crashes of small aircraft.

Even though the reactor core is protected, some of the piping and reactor cooling equipment, the auxiliary apparatus and the adjacent switchyard may be vulnerable to a direct hit. Nuclear power stations, however, are outfitted with multiple emergency cooling systems, as well as with emergency power supplies, should power be disabled. In the improbable event that all of these backup precautions were destroyed, the reactor core could overheat and melt. But even in this extreme case, which is similar to what occurred at Three Mile Island, the radioactive core materials would still be contained within the pressure vessel.

If nuclear plants have an Achilles' heel, it is the on-site temporary storage facilities for spent nuclear fuel. Although these depositories usually contain several used fuel assemblies and therefore more total radioactivity than a reactor does, most of the more dangerous radioactive isotopes in the old fuel have already decayed away. This is particularly true for the gaseous fission products that could get into the air, whose half-lives can be measured in months. Spent fuel assemblies that have been removed relatively recently from reactors are kept in deep pools of water to cool them and shield the radiation they emit. These open-air pools are surrounded by thick-walled, steel-lined concrete containers. After a few years, the materials are transferred into concrete, air-cooled dry fuel-storage casks.

FRENCH SOLDIER stands guard over an antiaircraft missile battery stationed near Europe's largest nuclear waste reprocessing plant in La Hague, Normandy.

Although cooling pools provide a relatively small and, hence, difficult target for terrorists, a pinpoint attack could drain a pool's water, causing the fuel to overheat and melt. Experts say that a standard fire hose would be enough refill the pool. Even if the fuel were to melt, little radioactive particulate would be produced that might become airborne, specialists say. An airliner crash into dry fuel-storage casks would probably just knock them aside. If any casks cracked, broken bits of oxidized fuel cladding could carry some radioactivity skyward, according to nuclear safety experts.

Some experts believe that the Nuclear Regulatory Commission will soon order the reinforcement of auxiliary nuclear plant equipment and waste storage facilities.

Should such a terrorist onslaught occur, plans are in place to evacuate nearby residents, although it must be said that critics claim these schemes to be impractical. It is thought, however, that there would be about eight to 10 hours available to get out safely, long before evacuees received a significant radioactive dose. The most severe potential adverse effect could be long-term contamination of the local area by airborne particulates, which would be expensive to clean up. *—The Editors*

which it is possible to envision fast-spectrum reactors that engineers believe will pose little chance of a meltdown. Further, nonreactive coolants such as inert gases, lead or lead-bismuth alloys may eliminate the need for a secondary coolant system and improve the approach's economic viability.

Nuclear energy has arrived at a crucial stage in its development. The economic success of the current generation of plants in the U.S. has been based on improved management techniques and careful practices, leading to growing interest in the purchase of new plants. Novel reactor designs can dramatically improve the safety, sustainability and economics of nuclear energy systems in the long term, opening the way to their widespread deployment. SA

MORE TO EXPLORE

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FRANCK PREVEL *AP Photo*

Why do we value fairness and cooperation over seemingly more rational selfishness? How can Darwinian generosity arise? Biologists and economists explain

THE ECONOMICS OF FAIR PLAY

By Karl Sigmund, Ernst Fehr and Martin A. Nowak
Illustrations by Brian Cronin

Imagine that somebody offers you $100. All you have to do is agree with some other anonymous person on how to share the sum. The rules are strict. The two of you are in separate rooms and cannot exchange information. A coin toss decides which of you will propose how to share the money. Suppose that you are the proposer. You can make a single offer of how to split the sum, and the other person—the responder—can say yes or no. The responder also knows the rules and the total amount of money at stake. If her answer is yes, the deal goes ahead. If her answer is no, neither of you gets anything. In both cases, the game is over and will not be repeated. What will you do?

Instinctively, many people feel they should offer 50 percent, because such a division is "fair" and therefore likely to be accepted. More daring people, however, think they might get away with offering somewhat less than half of the sum.

Before making a decision, you should ask yourself what you would do if you were the responder. The only thing you can do as the responder is say yes or no to a given amount of money. If the offer were 10 percent, would you take $10 and let someone walk away with $90, or would you rather have nothing at all? What if the offer were only 1 percent? Isn't $1 better than no dollars? And remember, haggling is strictly forbidden. Just one offer by the proposer: the responder can take it or leave it.

So what will you offer?

You may not be surprised to learn that two thirds of offers are between 40 and 50 percent. Only four in 100 people offer less than 20 percent. Proposing such a small amount is risky, because it might be rejected. More than half of all responders reject offers that are less than 20 percent. But here is the puzzle: Why should anyone reject an offer as "too small"? The responder has just two choices: take what is offered or receive nothing. The only rational option for a selfish individual is to accept any offer. Even $1 is better than nothing. A selfish proposer who is sure that the responder is also selfish will therefore make the smallest possible offer and keep the rest. This game-theory analysis, which assumes that people are selfish and rational, tells you that the proposer should offer the smallest possible share and the responder should accept it. But this is not how most people play the game.

The scenario just described, called the Ultimatum Game, belongs to a small but rapidly expanding field called experimental economics. A major part of economic theory deals with large-scale phenomena such as stock market fluctuations or gross national products. Yet economists are also increasingly fascinated by the most down-to-earth interactions—the sharing and helping that goes on within office pools, households, families and groups of children. How does economic exchange work in the absence of explicit contracts and regulatory institutions?

For a long time, theoretical economists postulated a being called *Homo economicus*—a rational individual relentlessly bent on maximizing a purely selfish reward. But the lesson from the Ultimatum Game and similar experiments is that real people are a crossbreed of *H. economicus* and *H. emoticus*, a complicated hybrid species that can be ruled as much by emotion as by cold logic and selfishness. An interesting challenge is to understand how Darwinian evolution would produce creatures instilled with emotions and behaviors that do not immediately seem geared toward reaping the greatest benefit for individuals or their genes.

Werner Güth of Humboldt University in Berlin devised the Ultimatum Game some 20 years ago. Experimenters subsequently studied it intensively in many places using diverse sums. The results proved remarkably robust. Behavior in the game did not appreciably depend on the players' sex, age, schooling or numeracy. Moreover, the amount of money involved had surprisingly little effect on results. In Indonesia, for instance, the sum to be shared was as much as three times the subjects' average monthly income—and still people indignantly refused offers that they deemed too small. Yet the range of players remained limited in some respects, because the studies primarily involved people in more developed countries, such as Western nations, China and Japan, and very often university students, at that.

Recently an ambitious cross-cultural study in 15 small-scale societies on four continents showed that there were, after all, sizable differences in the way some people play the Ultimatum Game. Within the Machiguenga tribe in the Amazon, the mean offer was considerably lower than in typical Western-type civilizations—26 instead of 45 percent. Conversely, many members of the Au tribe in Papua New Guinea offered more than half the pie. Cultural traditions in gift giving, and the strong obligations that result from accepting a gift, play a major role among some tribes, such as the Au. Indeed, the Au tended to reject excessively generous offers as well as miserly ones. Yet despite these cultural variations, the outcome was always far from what rational analysis would dictate for selfish players. In striking contrast to what selfish income maximizers ought to do, most people all over the world place a high value on fair outcomes.

Numerous situations in everyday life involve trade-offs between selfishness and fair play. A colleague, for example, invites you to collaborate on a project. You will be happy to do it, if you expect a fair return on your investment of time and energy or if he has helped you in the past. The pure Ultimatum Game, however, has artificial constraints that rarely apply in real-life interactions: haggling is impossible, people do not get to know each other, the prize vanishes if not split on the first attempt and the game is never repeated. But such constraints, rather than being a drawback, let us study human behavior in well-defined situations, to uncover the fundamental principles governing our decision-making mechanisms. The process is somewhat like physicists colliding particles in a vacuum to study their properties.

Theoretical economists **postulated a being** called *Homo economicus*—a rational individual relentlessly bent on maximizing a **purely selfish** reward.

Overview/*Fair Play*

- Universally across cultures, people value fairness highly and emotionally. Scientists study these behaviors in experiments such as the Ultimatum Game.
- In these experiments, players are often more generous than is predicted by game-theory analysis, which assumes that people selfishly seek to maximize their gains. Conversely, unfair play incites costly acts of revenge. The result is fairer play than is predicted.
- Humans could have evolved the emotions at work in these situations during the millions of years that we lived in small groups. Such emotions prompt us to behave in ways that would have benefitted either us or our group in the long run.

Getting Emotional

ECONOMISTS have explored a lot of variations of the Ultimatum Game to find what causes the emotional behavior it elicits. If, for instance, the proposer is chosen not by a flip of a coin but by better performance on a quiz, then offers are routinely a bit lower and get accepted more easily—the inequality is felt to be justified. If the proposer's offer is chosen by a computer, responders are willing to accept considerably less money. And if several responders compete to become the one to accept a single proposer's offer, the proposer can get away with offering a small amount.

These variations all point to one conclusion: in pairwise encounters, we do not adopt a purely self-centered viewpoint but take account of our co-player's outlook. We are not interested solely in our own payoff but compare ourselves with the other party and demand fair play.

Why do we place such a high value on fairness that we reject 20 percent of a large sum solely because the co-player gets away with four times as much? Opinions are divided. Some game theorists believe that subjects fail to grasp that they will interact only once. Accordingly, the players see the offer, or its rejection, simply as the first stage of an incipient bargaining process. Haggling about one's share of a resource must surely have been a recurrent theme for our ancestors. But can it be so hard to realize that the Ultimatum Game is a one-shot interaction? Evidence from several other games indicates that experimental subjects are cognitively well aware of the difference between one-shot and repeated encounters.

Others have explained our insistence on a fair division by citing the need, for our ancestors, to be sheltered by a strong group. Groups of hunter-gatherers depended for survival on the skills and strengths of their members. It does not help to outcompete your rival to the point where you can no longer depend on him or her in your contests with other groups. But this argument can at best explain why proposers offer large amounts, not why responders reject low offers.

Two of us (Nowak and Sigmund) and Karen M. Page of the Institute for Advanced Study in Princeton, N.J., have recently studied an evolutionary model that suggests an answer: our emotional apparatus has been shaped by millions of years of living in small groups, where it is hard to keep secrets. Our emotions are thus not finely tuned to interactions occurring under strict anonymity. We expect that our friends, colleagues and neighbors will notice our decisions.

If others know that I am content with a small share, they are likely to make me low offers; if I am known to become angry when facing a low offer and to reject the deal, others have an incentive to make me high offers. Consequently, evolution should have favored emotional responses to low offers. Because one-shot interactions were rare during human evolution, these emotions do not discriminate between one-shot and repeated interactions. This is probably an important reason why many of us respond emotionally to low offers in the Ultimatum Game. We may feel that we must reject a dismal offer in order to keep our self-esteem. From an evolutionary viewpoint, this self-esteem is an internal device for acquiring a reputation, which is beneficial in future encounters.

The Ultimatum Game, in its stark simplicity, is a prime example of the type of games used by experimental economists: highly abstract, sometimes contrived interactions between independent decision makers. The founders of game theory, the Hungarian mathematician

THE AUTHORS

KARL SIGMUND, ERNST FEHR and *MARTIN A. NOWAK* were invited to write an article on the Ultimatum Game, provided they could agree on how to share the work—not an easy task for people who know the rational solutions for problems in cooperation and fairness. Sigmund is professor of mathematics at the University of Vienna in Austria and also works at the Institute for Applied Systems Analysis in Laxenburg. He has written extensively on evolutionary game theory. Fehr is director of the Institute for Empirical Research in Economics at the University of Zurich in Switzerland. He uses game theory and experimental methods to understand how social preferences and rationality shape organizations, markets and societies. Nowak is head of the Theoretical Biology Program at the Institute for Advanced Study in Princeton, N.J. His work ranges from infectious diseases to evolutionary theory and human language. His most recent book is *Virus Dynamics* (with Robert M. May).

John von Neumann (one of the fathers of the computer) and the Austrian economist Oskar Morgenstern, collaborating in Princeton in the 1940s, used parlor games such as poker and chess for illustrating their ideas. Parlor games can certainly be viewed as abstractions of social or economic interactions, but most of these games are zero-sum: the gains of one player are the losses of another. In contrast, most real-life economic interactions are mixed-motive: they display elements of cooperation as well as competition. So-called Public Goods games model that situation.

Revenge Is Sweet

IN ONE of the simplest Public Goods games, four players form a group. The experimenter gives each player $20, and they have to decide, independently of one another, how much to invest in a common pool. The experimenter doubles the common pool and distributes it equally among all four group members.

If every player contributes the full $20, they all double their capital. Cooperation is highly rewarding. But the temptation to hold back on one's own contribution is strong. A selfish player ought to contribute nothing at all, because for every dollar he invests, only 50 cents return to his account. (The money is doubled by the experimenter but then divided by four among the players.) The experimenter makes sure that the players fully understand this, by asking them to figure out how much each would end up with if, say, Alice contributed $10, Bob and Carol only $5 each, and Dan nothing at all. After this preparation, the game is played for real. If everyone followed the selfish rational strategy predicted by economics, nothing would be invested and nobody would improve their $20 stake. Real people don't play that way. Instead many invest at least half of their capital.

If the same group repeats the game for 10 rounds, subjects again invest roughly half of their capital during the first rounds. But toward the end, most group members invest nothing. This downhill slide from a high level of cooperation used to be interpreted as a learning process: players learn the selfish strategy the hard way—through a series of disappointing experiences. But this cannot be the right explanation, because other experiments have shown that most players who find themselves in new groups, with co-players they have not met before, start out again by contributing a lot. What explains these behaviors?

Experiments conducted by one of us (Fehr) and Simon Gächter from the University of St. Gallen in Switzerland show that the Public Goods game takes a dramatic turn if a new option is introduced—that of punishing the co-players. In these experiments, players may impose fines on their co-players at the end of each round, but only at a cost. If Alice wants to impose a fine of $1 on Dan, Alice has to pay 30 cents. Both the dollar and the 30 cents go back to the experimenter. The cost makes the act of punishment unjustifiable from the selfish point of view (Alice reduces her capital and gains nothing in return). Nevertheless, most players prove very willing, and even eager, to impose fines on co-players who lag behind in their contributions. Everyone seems to anticipate this, and even in a game of one round, less defection occurs than usual. Most significant, if the game is repeated for a known, preset number of periods, the willingness to contribute does not decline. Quite the contrary—the contributions to the common pool rise over time, and in the last few rounds more than 80 percent of all group members invest the whole capital: a striking difference to the outcome of the game without punishment.

In a repeated game, players can see punishment as a shrewd, selfish investment in co-player education: Tightwads are taught to contribute to the general

In pairwise encounters, we do not adopt a purely self-centered viewpoint but take account of **our co-player's outlook.**

benefit. Incurring costs to punish cheapskates can yield profits in the long run. But a recent variation of the Public Goods game shows that this economic aspect is only a side issue. In this version, numerous groups of four players are assembled, and after every round players are redistributed so that no two people ever meet twice. The punishment pattern (and also the high level of investments) does not change—free riders are punished as severely as when everyone stays in the same group, and again investments start high and may rise.

This result is astonishing, because the "educational payoff" has been eliminated. As before, being fined usually increases a player's future investment, but this increase never benefits the player who imposes the fine. Nevertheless, a lot of players show great eagerness to punish defectors. Participants seem to experience a primal pleasure in getting even with free riders. They seem to be more interested in obtaining personal revenge than in increasing their overall economic performance.

Why are so many players willing to pay the price to punish free riders without reaping any material benefit from it? Evolutionary economist Herbert Gintis of the University of Massachusetts has recently shown that this behavior can provide fitness advantages. In his model, social groups with an above-average share of punishers are better able to survive events such as wars, pestilence and famines that threaten the whole group with extinction or dispersal. In these situations, cooperation among self-interested agents breaks down because future interactions among group members are highly improbable. Punishers discipline the self-interested agents so that the group is much more likely to survive. Subjects who punish are not, of course, aware of this evolutionary mechanism. They simply feel that revenge is sweet.

People expect fairness and solidarity within most groups, be it children in a summer camp or capos in the Mafia. Ultimately, moral guidelines determine an essential part of economic life. How could such forms of social behavior evolve? This is a central question for Darwinian theory. The prevalence of altruistic acts—providing benefits to a recipient at a cost to the donor—can seem hard to reconcile with the idea of the selfish gene, the notion that evolution at its base acts solely to promote genes that are most adept at engineering their own proliferation. Benefits and costs are measured in terms of the ultimate biological currency—reproductive success. Genes that reduce this success are unlikely to spread in a population.

Darwinian Generosity

IN SOCIAL INSECTS, the close relatedness among the individuals explains the huge degree of cooperation. But human cooperation also works among nonrelatives, mediated by economic rather than genetic ties. Nevertheless, biologists have shown that a number of apparently altruistic types of behavior can be explained in terms of biological success. (Others argue that a second form of evolution—an evolution of ideas, or "memes"—is at work. See "The Power of Memes," by Susan Blackmore; SCIENTIFIC AMERICAN, October 2000.)

It may seem callous to reduce altruism to considerations of costs and benefits, especially if these originate in biological needs. Many of us prefer to explain our generous actions simply by invoking our good character. We feel better if we help others and share with them. But where does this inner glow come from? It has a biological function. We eat and make love because we enjoy it, but behind the pleasure stands the evolutionary program commanding us to survive and to procreate. In a similar way, social emotions such as friendship, shame, generosity and guilt prod us toward achieving biological success in complex social networks.

Centuries ago philosophers such as David Hume and Jean-Jacques Rousseau emphasized the crucial role of "human nature" in social interactions. Theoretical economists, in contrast, long preferred to study their selfish *Homo economicus*. They devoted great energy to theorizing about how an isolated individual—a Robinson on some desert island—would choose among different bundles of commodities. But we are no Robinsons. Our ancestors' line has been social for some 30 million years. And in social interactions, our preferences often turn out to be far from selfish.

Ethical standards and moral systems differ from culture to culture, but we may presume that they are based on universal, biologically rooted capabilities, in the same way that thousands of different languages are based on a universal language instinct. Hume and Rousseau would hardly be surprised. But today we have reached a stage at which we can formalize their ideas into game-theory models that can be analyzed mathematically and tested experimentally. SA

MORE TO EXPLORE

Games of Life: Explorations in Ecology, Evolution and Behavior. Karl Sigmund. Penguin, 1995.

Game Theory and the Social Contract: Just Playing. Kenneth G. Binmore. MIT Press, 1998.

Fairness versus Reason in the Ultimatum Game. Martin A. Nowak, Karen M. Page and Karl Sigmund in *Science,* Vol. 289, pages 1773–1775; September 8, 2000.

Cooperation and Punishment in Public Goods Experiments. Ernst Fehr and Simon Gächter in *American Economic Review,* Vol. 90, No. 4, pages 980–994; September 2000.

In Search of Homo Economicus: Behavioral Experiments in 15 Small-Scale Societies. Joseph Henrich, Robert Boyd, Samuel Bowles, Colin Camerer, Ernst Fehr, Herbert Gintis and Richard McElreath in *American Economic Review,* Vol. 91, No. 2, pages 73–78; May 2001.

WORKINGKNOWLEDGE

GAS MASKS

Breathing Easier?

The spread of anthrax in the U.S. that began in October has spurred many people to buy gas masks. But the gear's effectiveness may be misunderstood.

A mask's filter canister is intended to stop particles such as anthrax, chemicals such as nerve gas, and germs such as smallpox. The respirators come as face masks that protect the mouth, nose and eyes and as hoods that envelop the head.

U.S. certification is done by the National Institute for Occupational Safety and Health (NIOSH) and the armed services. Two key parameters are the size of the smallest particle the filter traps (the best are 0.3 micron) and the efficiency of gases the filter removes, rated at 95, 99 or 99.97 percent.

Equally crucial, however, are proper fit and training. Consumers should be fitted by a supplier to prevent leaks along the seal. They also should be taught how to put the mask on quickly and snugly, which takes practice. Further, people with respiratory problems may have difficulty using a mask, which demands three times the lung power of normal breathing. Masks will not seal against beards, sideburns or facial scars. And filters may have to be replaced after only several hours or days of constant use.

Two weeks after the U.S. anthrax scare began, orders at MSA, Inc., in Pittsburgh, which manufactures gas masks primarily for the leading markets—the military, police and firefighters, and industries from mining to automobile painting—were up "a lot," says product group manager Ken Bobetich. So were attempts to sell poor products. Just five manufacturers make NIOSH-certified military-style masks, yet scores of companies were peddling respirators on the Web for as little as $29. Consumers should not buy uncertified or old products, Bobetich warns. Because filters are chemically activated, "the typical shelf life is only three to four years," he notes. A good filter alone costs $30. Anything advertised as military surplus is too old. A current, approved mask sells for $150 to $250, Bobetich says. If you scrimp, he adds, "you'll get what you pay for"—greater risk to your life. —*Mark Fischetti*

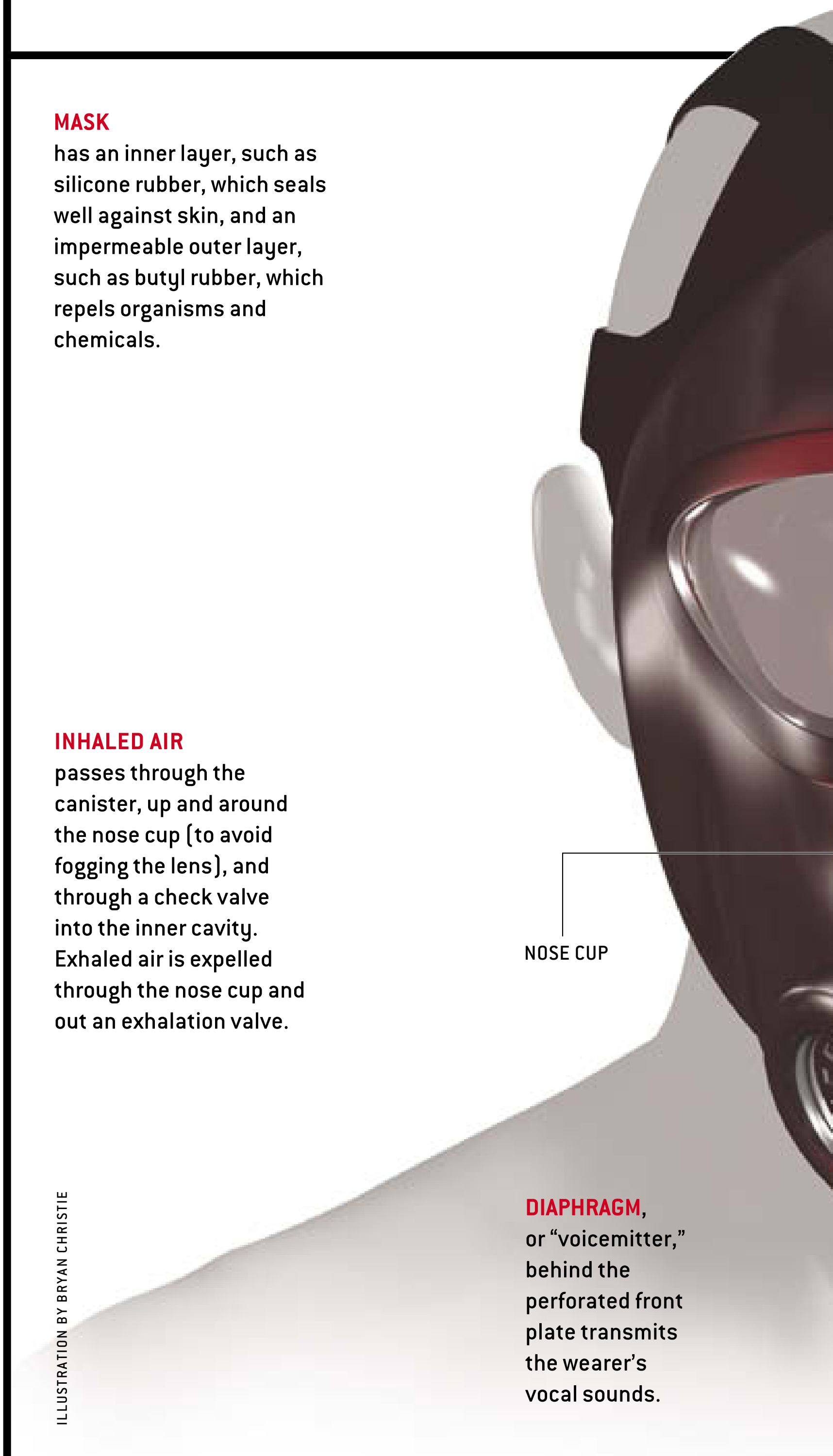


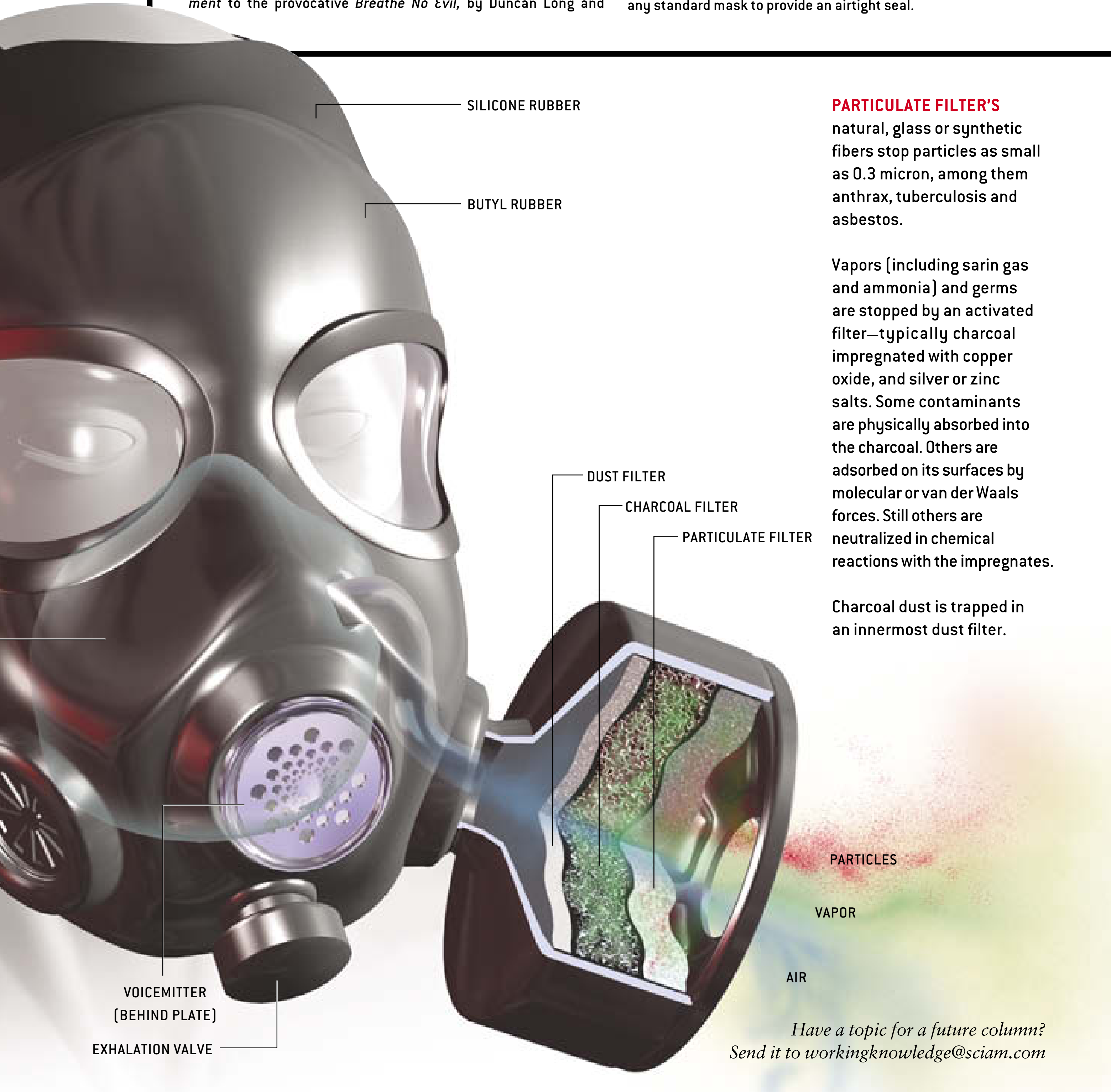
ILLUSTRATION BY BRYAN CHRISTIE

DID YOU KNOW . . .

➤ ACTIVE HISTORY: Chemically activated filters were used in some of the first gas masks, issued to troops during World War I. According to a U.S. Army warfare handbook, an early "hypo helmet" of 1915 neutralized chlorine with sodium thiosulfate. Sporadic events ever since have underlined the need to maintain up-to-date countermeasures: mustard gas was found during the Iran-Iraq war; anthrax leaked from a Soviet chemical plant in Sverdlovsk in 1979; sarin was released into a Tokyo subway by the Aum Shinrikyo cult in 1995.

➤ PROFITEERING: Hot survival-gear books range from the encyclopedic *Jane's NBC* [nuclear-biological-chemical] *Protection Equipment* to the provocative *Breathe No Evil,* by Duncan Long and Stephen Quayle. Radius Engineering sells a $4,500 "life cell"—a four-foot-diameter filtering system for your self-sealed living room, powered by 500 pounds of batteries. Polaris International offers a $1,950 "bio shelter"—a plastic bubble for the den, fed by an air-filtration system, into which your family can step once the germ attacks begin.

➤ CAN'T SAVE THE KIDS: Manufacturers generally don't make gas masks for children, and regulators wouldn't approve them. Both groups maintain that breathing through a mask is too strenuous for children and that children's facial structures vary too widely for any standard mask to provide an airtight seal.



PARTICULATE FILTER'S natural, glass or synthetic fibers stop particles as small as 0.3 micron, among them anthrax, tuberculosis and asbestos.

Vapors (including sarin gas and ammonia) and germs are stopped by an activated filter—typically charcoal impregnated with copper oxide, and silver or zinc salts. Some contaminants are physically absorbed into the charcoal. Others are adsorbed on its surfaces by molecular or van der Waals forces. Still others are neutralized in chemical reactions with the impregnates.

Charcoal dust is trapped in an innermost dust filter.

Have a topic for a future column? Send it to workingknowledge@sciam.com

The Glass House in the Desert

BIOSPHERE 2 COURTS SCIENTISTS AND TOURISTS ALIKE **BY MARGUERITE HOLLOWAY**

It is a brilliant hot morning in the desert north of Tucson, Ariz., and the sun blazes down on a dozen or so people as they wend their way through a savanna and around a marsh, an ocean, and miles of pipes, channels, steel struts and glass panels. Half factory, half unkempt-looking greenhouse, the great glass structure that is Biosphere 2 is open to the public, to students and to scientists conducting climate change experiments. And on this day the rain forest, usually closed to visitors, is also open.

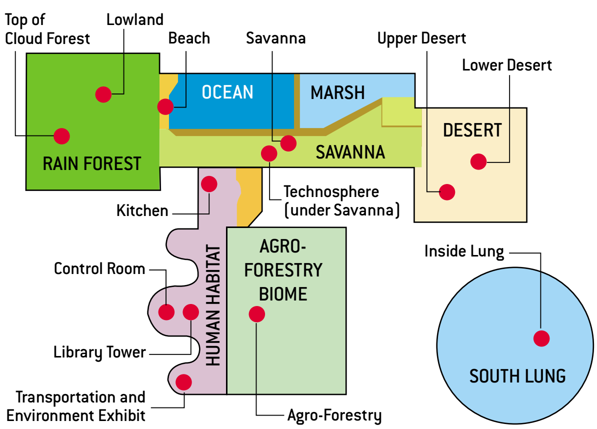
The group moves from behind the scenes—from the concrete underbelly of a man-made mountain and its 55-foot waterfall—out into the steamy forest, walking along wooden boards, sweltering in 85 degrees Fahrenheit, 95 percent humidity. The Arizona desert is no longer visible through the tangle of sugar palms, banana and Kapok trees (the latter have to be trimmed so they don't burst through the glass ceiling), and other vegetation. William Young, a guide, explains that researchers have just finished subjecting the plants to 30 days of drought followed by seven days of rain over several months to learn how these conditions affect carbon dioxide intake. Because Biosphere 2 is a closed system, rainfall and atmospheric makeup can be regulated and measured, allowing scientists to conduct controlled experiments.

Once finished with the pleasantly mosquito-free rain forest, visitors amble next door to see and hear the softly crashing waves of the tiny ocean. Here researchers are examining the impact of rising CO_2 levels on 25 or so species of coral. One such study has already shown that the corals cannot acclimate to the increase and begin to die off. These corals—and the abundant fish—are also visible from a lower, underwater level, accessible from outside Biosphere 2.

The group is then led behind the scenes again, through the industrial passageways under and beside the various ecosystems. It is somewhat like being on a movie set: what seems real is sustained by an array of devices. Nature and artifice hand in hand. Young mentions the enormous cost of controlling the tide and keeping the various plots at the right temperature; the energy bill runs about $50,000 a month, according to the communications office. Without the cooling and ventilation system, things get hot quickly under the unrelenting desert sun. Once when the local power grid failed, Young recalls, the rain forest shot from 85 to 120 degrees F in just 15 minutes.

The "Under the Glass" tour finishes with a quick shuffle through a pan of water and detergent so no one inadvertently tracks exotic plant material into the desert. And then the group is back in the dry heat, free to wander to nearby exhibits or to take another walking tour, this time of the grounds.

For many of the 180,000 or so annual visitors, part of Biosphere 2's allure lies in its first mission as an experimental habitat for space travelers. To that end, the internal tours of the 3.15-acre structure—which were started in late 1999—allow visitors to see not only the different ecosystems but also the living quarters, uniforms and other



BIOSPHERE 2 covers 3.15 acres and includes five biomes. The structure is ventilated by two nearby domed "lungs," one of which is shown here.

DAVE G. HOUSER *Corbis* (*photograph*); BIOSPHERE 2 CENTER, JOHNNY JOHNSON (*floor plan*)

gear of the original Biospherians, as they are called. Biosphere 2 was built in the late 1980s by Texan oil magnate Edward P. Bass as a means to test whether life in an elaborate spaceship or a similar module on other planets could be sustainable. In 1991 eight people were sealed inside for two years. They were to grow their own food, to live entirely self-sufficiently. The experiment failed as levels of oxygen fell, food production faltered and air had to be pumped in. Biosphere 2 was ultimately ridiculed as a research debacle, as extravagant pseudoscience.

Shaking this image has not been easy, but Columbia University, which began to manage Biosphere 2 in 1996, is trying. Scientists are conducting experiments, and about 100 students from Columbia and other institutions are accepted every semester for earth science and related studies. The university recently renewed its management contract through 2010 and began building more dorms, referring to the site as its western campus; it ultimately may decide to buy Biosphere 2 at the end of the current contract.

It is clear that education and research are a focus these days. The "Under the Glass" tour guides describe some of the current research projects, and Biosphere 2 has very good displays on climate change and on the evolution of reefs. A guided walking tour of the grounds includes an informative greenhouse exhibit of plants that have been useful to humans as well as detailed information on the materials used in Biosphere 2 and its construction. And a new telescope is open

FEATURED STORY

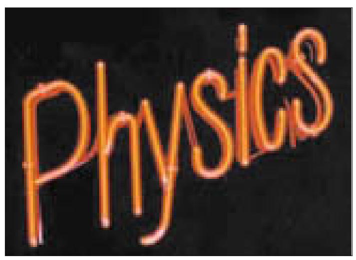
California Heats Up over Natural Steam

This fall Santa Rosa, Calif., came yet one step closer to pumping its treated wastewater into the ground. The city settled the fifth lawsuit that had threatened to block construction of a pipeline that will carry the water east to the Geysers geothermal steam field in Napa Valley. Once injected into the ground, this wastewater will replenish the steam that provides energy for cities in and around the San Francisco Bay Area. Unfortunately, the injected water will also create an undesirable by-product: flurries of very small earthquakes.

ASK THE EXPERTS

How do neon lights work? If neon is an inert gas, doesn't that mean it should stay inert, even if a current is passed through it?

Eric Schiff, chair of the department of physics at Syracuse University, explains.



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VOYAGES

RAIN FOREST once housed animals, but the monkeys got into mischief and the insects were devoured by one species of ant.

for public nightly viewing programs. Yet the site retains a somewhat light feeling, almost as if it were a desert spa or resort. A large sign at the entrance to the grounds announces a $75-a-night special at the on-site hotel, and the walking tour passes tennis courts, three gift shops—two of them just several dozen yards apart—and reminders of corporate sponsorship.

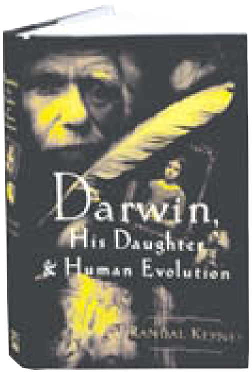
Biosphere 2 is located about 30 miles north of Tucson, a straightforward drive along Highway 77 toward Oracle. From Phoenix, take Interstate 10 east to the Tangerine Road exit and follow Tangerine Road until it hits Highway 77, then drive north; the trip takes about 90 minutes. The site is open every day, except Christmas, from 8:30 A.M. until 5 P.M., and there are frequent walking tours. The entrance fee ranges from $12.95 for adults to $6 for children ages six through 12. The "Under the Glass" tours, which cost $10 a person, are less frequent and are dependent on demand, so you might want to make a reservation: call 520-896-5465 or 800-828-2462. For more information, visit the Web site at www.bio2.edu SA

Marguerite Holloway teaches at the school of journalism at Columbia University.

ROGER RESSMEYER *Corbis*

The First Evolutionary Psychologist

CHARLES DARWIN SOUGHT CLUES TO HUMAN NATURE BY STUDYING THE BEHAVIOR OF HIS OWN CHILDREN AND OTHER WILD ANIMALS **BY RICHARD MILNER**



DARWIN, HIS DAUGHTER, AND HUMAN EVOLUTION
By Randal Keynes
Riverhead Books, Penguin Putnam, 2002 ($26.95)

When descendants of Charles Darwin get together, some still tell the story of a long-ago servant who expressed pity for the family patriarch. The poor man, she said, was so idle that she saw him staring at an ant heap for a whole hour. Darwin's full-time, self-created job, of course, was to observe every animate creature, from the ants and bees in his garden, to giant tortoises in the Galápagos, to his own family. He even published a monograph on the behavior of his infant children.

Randal Keynes, a great-great-grandson of Charles Darwin (and also a descendant of John Maynard Keynes), has crafted a superb intellectual and social history about Darwin's quiet years (c. 1842–1882) at his country estate, long after his HMS *Beagle* adventures. Charles and Emma Wedgwood Darwin produced 10 children but lost three—an infant daughter and son, and the bright and charming 10-year-old Annie, whose death plunged her parents into profound bereavement. Annie's fatal tuberculosis (a cogent diagnosis suggested by Keynes, although it was problematic in Darwin's day) was the most wrenching event of the naturalist's middle age.

Among his family's heirlooms, Keynes discovered Annie's writing case, containing her goose-quill pens and stationery, a lock of her hair, and her father's mournful yet objective daily notes on her deteriorating condition. (The British edition of the book is titled *Annie's Box*.) Initially inspired and affected by these mementos, Keynes came to realize that "Charles's life and his science was all of a piece." With impeccable scholarship, he has woven clips from Victorian magazines, contemporary poems and novels, family letters and keepsakes, and even recollections of living people into a stylish narrative that is both moving and thoroughly documented.

IN 1849 ANNIE DARWIN sat for this daguerreotype, which her father, Charles, was later "so thankful to have."

Darwin had often wondered whether his powerful affection for family could be explained in evolutionary terms. His then radical conclusion: our deepest emotions are rooted in the evolution of primate social organization. If we had descended from bees instead of from apes, he once opined, "there can hardly be a doubt that our unmarried females would, like the worker-bees, think it a sacred duty to kill their brothers, and mothers would strive to kill their fertile daughters; and no one would think of interfering."

According to Keynes, Darwin was at a loss to understand why most naturalists at the time thought they saw evidence of ubiquitous, benevolent design in a world so full of pain, death and disease. "There seems to me," he wrote, "too much misery in the world" for a loving deity to have designed it that way. He had witnessed genocide of the Indians in Argentina and the torture of slaves in Brazil. He had written of wasps whose larvae devour a living caterpillar from within, leaving the beating heart for last. With the slow death

ENGLISH HERITAGE PHOTOGRAPHIC LIBRARY; BOOK PHOTOGRAPH BY BETH PHILLIPS of Annie, the misery became personal.

Some contemporary critics painted Darwin as a cold intellect with no place for love in his famous "struggle for existence." Keynes shows he was actually a man of uncommon warmth. While he was "anxious to observe accurately the expression of a crying child," according to his son Francis, he usually found that "his sympathy with the grief spoiled his observation." To comfort his friend Sir Joseph Hooker when the botanist's young son fell ill, Darwin drew on his own agonizing deathwatch of Annie: "Much love, much trial, but what an utter desert is life without love."

As the first evolutionary psychologist, Darwin was breaking new ground by seeking the roots of human behavior in our species' mammalian history. In *On the Origin of Species* (1859), he had predicted that "psychology will be based on a new foundation," which he attempted to establish in his 1872 book *The Expression of the Emotions*. Comparing the behavior of dogs, cats, monkeys, orangutans, infants and tribal peoples from all over the world, he argued that human affection, sympathy, parental love, morality and even religious feelings had gradually developed from a primate base. Such "evil passions" as rage and violence were also part of Grandfather Baboon's legacy.

Once I had a rare chance to examine Darwin's printer's proofs of this treatise on comparative psychology, which contain his handwritten corrections. The title, as printed, was *The Expression of the Emotions in Man and Lower Animals*. Darwin had emphatically crossed out the word "lower." SA

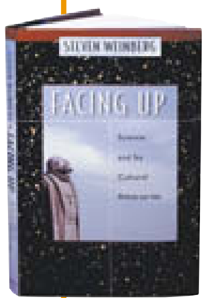
Historian of science Richard Milner, who is preparing a new edition of his Encyclopedia of Evolution, *frequently performs his one-man musical, "Charles Darwin: Live & In Concert."*

BETH PHILLIPS

THE EDITORS **RECOMMEND**

FACING UP: SCIENCE AND ITS CULTURAL ADVERSARIES

by Steven Weinberg. Harvard University Press, Cambridge, Mass., 2001 ($26)



Weinberg's thesis in these essays is that the laws of nature, insofar as they are known, "are impersonal, with no hint of a divine plan or any special status for human beings." Each essay, he says, "struggles with the necessity of facing up to these discoveries." Weinberg is an eminent physicist—sharer of the Nobel Prize for Physics in 1979 and professor of physics and astronomy at the University of Texas at Austin—who some 20 years ago started speaking and writing on broader subjects, notably "on the follies that I found in the attitudes toward science of many sociologists, philosophers, and cultural critics, and on the ancient tension between science and religion." The 23 pieces gathered here, learned and deftly written, are among the results of that undertaking.

THE WIZARDS OF LANGLEY: INSIDE THE CIA'S DIRECTORATE OF SCIENCE AND TECHNOLOGY

by Jeffrey T. Richelson. Westview Press, Boulder, Colo., 2001 ($30)

Richelson shines a spotlight on a group unknown to most Americans: the Central Intelligence Agency's Directorate of Science and Technology. Robert Gates, former CIA director, has called the directorate's staff "the wizards ... who pioneered reconnaissance aircraft like the U-2 and SR-71, photographic satellites from the KH-4 to KH-11, an amazing array of signals intelligence satellites." Richelson, a senior fellow at the National Security Archive, describes not only the directorate's achievements but also its mistakes and focuses on a number of the people involved in its activities. The directorate, he says, "has had a dramatic impact on the collection and analysis of intelligence."

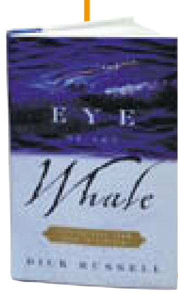
THE INVENTION OF CLOUDS: HOW AN AMATEUR METEOROLOGIST FORGED THE LANGUAGE OF THE SKIES

by Richard Hamblyn. Farrar, Straus and Giroux, New York, 2001 ($24)

The amateur meteorologist was Luke Howard, a London chemist who gave the three basic cloud families names that survive today: cirrus, cumulus and stratus. Howard had, Hamblyn writes, "the penetrating ... insight that clouds have many individual shapes but few basic forms." The author, who supervises undergraduates in English and the history of science at the University of Cambridge, weaves several strands—Howard's work, the lively London science scene 200 years ago and the development of meteorology—into a grand story.

EYE OF THE WHALE: EPIC PASSAGE FROM BAJA TO SIBERIA

by Dick Russell. Simon & Schuster, New York, 2001 ($35)



The whale is *Eschrichtius robustus,* the gray whale of the Eastern Pacific, which makes "a twice-annual migration that must be regarded as one of the most spectacular achievements on the planet." Swimming close to the shore, some 26,000 grays travel from breeding areas in the central Baja California region of Mexico to Arctic feeding grounds near the Bering Strait and back—a minimum of 5,000 miles each way. Environmental journalist Russell writes sensitively about the past, present and uncertain future of these remarkable animals.

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

PUZZLING**ADVENTURES**

Pinpointing a Polar Bear

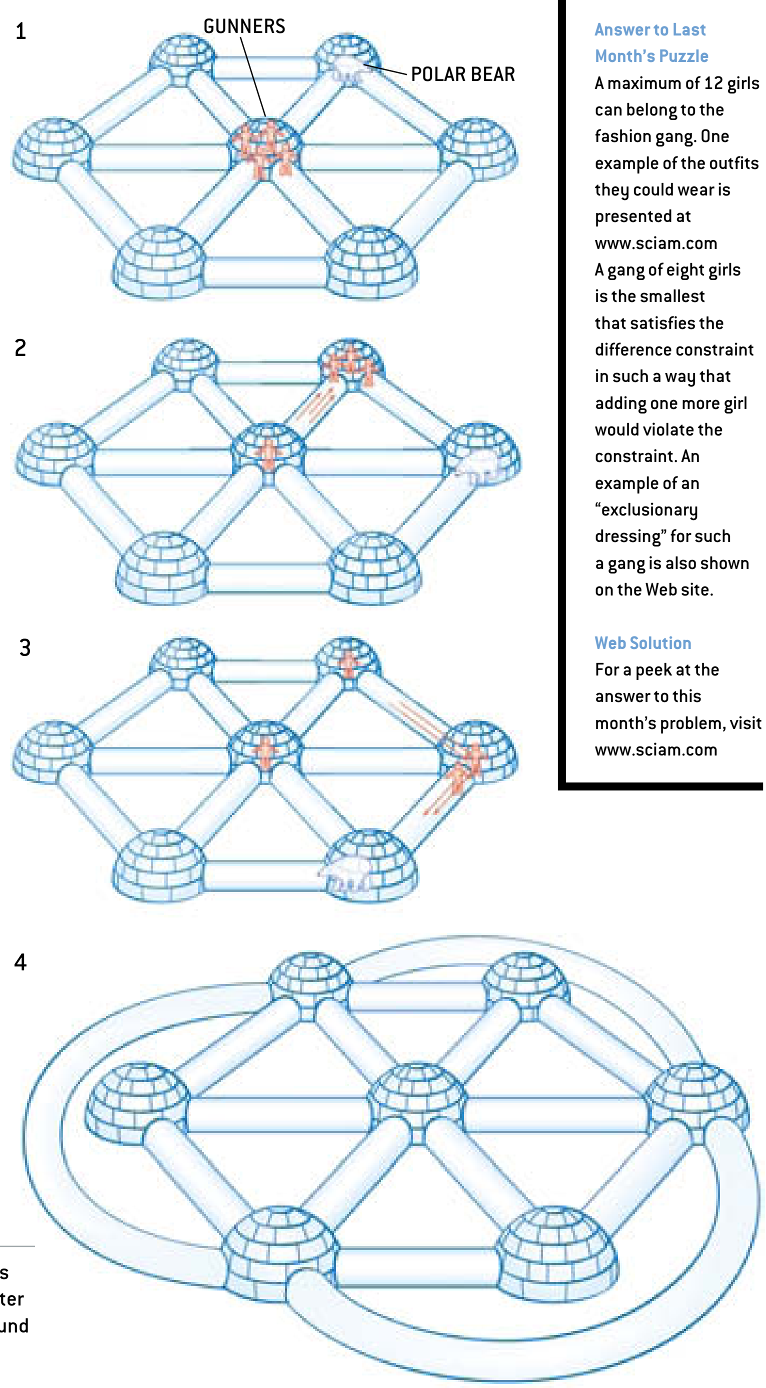
BY DENNIS E. SHASHA

Imagine a research center in the Canadian Arctic. Unoccupied in the winter, the center consists of seven laboratory igloos linked by corridors. Each corridor connects two igloos. During a particularly harsh winter, a polar bear breaks into one of the igloos and starts wandering through the empty complex. The scientists must send a team to tranquilize the bear with a dart gun, but they don't know how many gunners to send.

Safety rules specify that at least two gunners are needed to search an igloo and that they must approach the room together from the same corridor. But one person is enough to prevent the bear from coming into an igloo that has already been searched. A polar bear would find the corridors claustrophobic, so it would not hide there. Instead it would run from igloo to igloo, and because the animal moves so quickly (much faster than the gunners) the transit time is essentially zero.

Suppose that the complex has a wheel-and-spoke pattern, with one igloo at the center and six at the perimeter. In this case, four gunners are enough to track down the bear [*see illustrations 1 through 3 at right*]. But what if the scientists have forgotten the exact layout of the research center? All they know for certain is that there is at most one corridor connecting one igloo to another and that the corridors don't meet or cross one another. (Mathematicians call this topology a planar graph.) An example of such a pattern is shown in illustration 4. The gunners can start at any igloo. What is the fewest number of gunners that can be sent?

Now suppose there are 100 igloos arranged in a rectangular grid. Each igloo has corridors leading to its horizontal and vertical neighbors (no diagonal corridors are allowed). What is the smallest team of gunners that can do the job? SA



TO FIND A POLAR BEAR in a wheel-and-spoke pattern, four gunners begin at the central igloo (*1*). Three gunners head for one of the outer igloos, leaving one gunner behind (*2*). Then two gunners move around the perimeter in either direction (*3*). But how many gunners are needed for a generalized planar graph such as the one shown (*4*)?

SARA CHEN

Answer to Last Month's Puzzle

A maximum of 12 girls can belong to the fashion gang. One example of the outfits they could wear is presented at www.sciam.com

A gang of eight girls is the smallest that satisfies the difference constraint in such a way that adding one more girl would violate the constraint. An example of an "exclusionary dressing" for such a gang is also shown on the Web site.

Web Solution

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

Torre Adoring

PART OF HIS SUCCESS CAN BE ATTRIBUTED TO THE MANAGER'S USE OF YANKEE INGENUITY IN APPLYING SOME SIMPLE RULES BY STEVE MIRSKY

In February 2000 I was loitering at the American Association for the Advancement of Science meeting, where I stumbled onto a session on the science of baseball. One of the speakers was *Washington Post* baseball writer Thomas Boswell, who talked about New York Yankees manager Joe Torre's exemplary use of the principles put forth in the book *Influence: The Psychology of Persuasion,* by social psychologist Robert B. Cialdini. For anyone who's been living in a cave (a phrase that used to describe ignorance and not malevolence), the Yankees have been wildly successful under Torre, winning four of five World Series before coming *thisclose* while losing in 2001. After Boswell's talk, we got Cialdini to write an article for *Scientific American,* and that's why I owe Joe. (And Boswell.)

Cialdini codified six basic rules of persuasion (discussed at length in "The Science of Persuasion," February 2001). The first is reciprocity: Who are you going to drive to the airport, your mooching brother-in-law or your friend Paul who took you to the fifth game of the World Series? (Thank you, Paul.) Second, consistency: make a commitment, especially in public, and the urge to behave consistently with that commitment will tug at you like a Rottweiler. Third, social validation: if all your friends are doing it, jumping off that building might actually be weirdly tempting, Mom. Fourth, liking: obviously, you're more likely to extend yourself for someone you like. Fifth, authority: Are you going to believe me or Robert Cialdini, Ph.D.? And sixth, scarcity: Which do you want more, a piece of cheesecake or the *last* piece of cheesecake?

The reciprocity rule explains my feeling of indebtedness to Torre. To pay him back, I'll devote the rest of this space (which I guess means I owe him again, but I can't think about that right now) to a discussion of how Torre used Cialdini's rules so effectively in persuading the Yankees to win the 2001 American League Championship Series against the Seattle Mariners, whose manager, Lou Piniella, misused the rules (but was named AL manager of the year anyway, a vote taken before the playoffs).

The Yankees took the first two games of their best-of-seven playoff series, in Seattle. The next three games would be played in New York. If the Yankees won two of those three home games, the series would end before returning to Seattle. Immediately following Game 2, Piniella told reporters: "I want you all to print this. We're going to be back here for Game 6. Write it."

ILLUSTRATION BY MATT COLLINS; PHOTOGRAPH BY FRANK VERONSKY

On the surface, such a statement seems merely to be a display of a manager's confidence in his team. The ploy, however, fails on at least two counts. By forcing a commitment onto his players' backs, Piniella abused the reciprocity rule: he took a commitment from them that was not freely given. This coercion also violates the spirit of the consistency rule, as the players had to try to follow through on a pledge made by somebody else. And the potential cost of failure is the very visible erosion of the manager's authority.

Torre, however, is a master of Cialdini's rules. The Yankees lost Game 3. Before the fourth game, Torre simply told his players not to bring luggage the next day for a possible return to Seattle after Game 5. He thus had each luggageless player make a public (within the clubhouse—the press only found out later) commitment to the team to dispatch Seattle before a sixth game would be necessary. Social validation also comes into play, because each player sees *all* his teammates leaving their luggage home. And the potential cost of failure is minimal—go home and pack, leave with no luggage, whatever.

Torre's Yankees did indeed win in five games, not needing their luggage until later in the week when they flew to Arizona to begin a World Series that they would ultimately lose in the last inning of the last possible game. Because as Casey Stengel's dictum clearly states, good pitching will always stop good hitting, and vice versa. SA

How do seedless fruits arise, and how are they propagated?

—M. Charbonneau, Clifton Park, N.Y.

Benjamin Burr and Frances Burr, biologists at Brookhaven National Laboratory, offer this explanation:

Fruit development normally begins when one or more egg cells in the ovular compartment of the flower are fertilized by sperm nuclei from pollen. In some plants, however, fruit develops without fertilization, a trait called parthenocarpy. Parthenocarpic fruit has advantages over seeded fruit: longer shelf life and greater consumer appeal.

The most frequent reasons for lack of seed development are pollination failure or nonfunctional eggs or sperm. In many plants, self-incompatibility genes limit successful fertilization to cross-pollination between genetically different male and female parents. This property is exploited by citrus farmers who grow seedless fruits, such as navel oranges and clementines. These cultivars fail to set seed when they are planted in orchards of identical plants (clones). They are parthenocarpic, though, so they still produce fruit. Such trees do not require seed for propagation. In fact, propagation by seed would be disadvantageous because the progeny would differ from the parent. Rather nurserymen frequently propagate fruit trees asexually, usually by grafting.

Another reason for lack of successful fertilization is chromosomal imbalance. For example, the common banana is triploid: it has three sets of chromosomes. Instead of having one set of chromosomes from each parent, it has two sets from one parent and one set from the other parent. Triploids seldom produce eggs or sperm that have a balanced set of chromosomes, and so successful seed set is very rare. Bananas can also be parthenocarpic, in which case they are asexually propagated. Side shoots or suckers at the base of the main stalk are replanted to continue the cultivar. Growers also propagate bananas by tissue culture.

Seedless watermelons are particularly interesting because they must be propagated by seed, and yet growers can still exploit parthenocarpy. One way to make them is to produce triploid seed. As with bananas, triploid watermelons cannot produce functional seed, but they do develop good fruit through parthenocarpy. Plant breeders produce triploid seed by crossing a normal diploid parent with a tetraploid parent, which itself is made by genetically manipulating diploids to double their chromosome number. This manipulation has to be performed every generation, so it is a somewhat expensive proposition but still worthwhile. SA

For the complete text of this and many other answers from scientists in diverse fields, visit Ask the Experts (www.sciam.com/askexpert).

WORLD WITHOUT ALGEBRA

MICHAEL CRAWFORD

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