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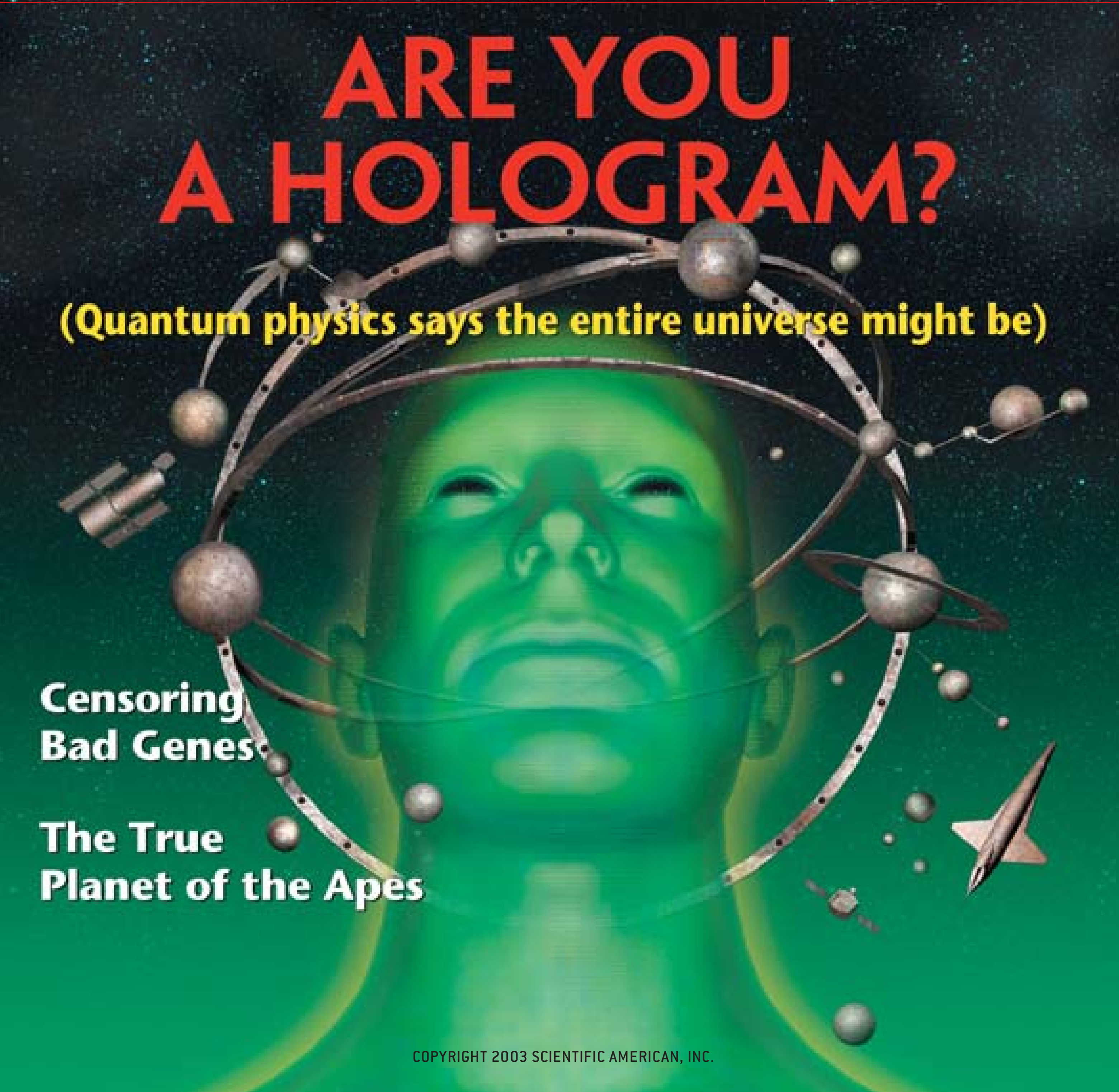

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(Quantum physics says the entire universe might be)

Censoring Bad Genes

The True Planet of the Apes

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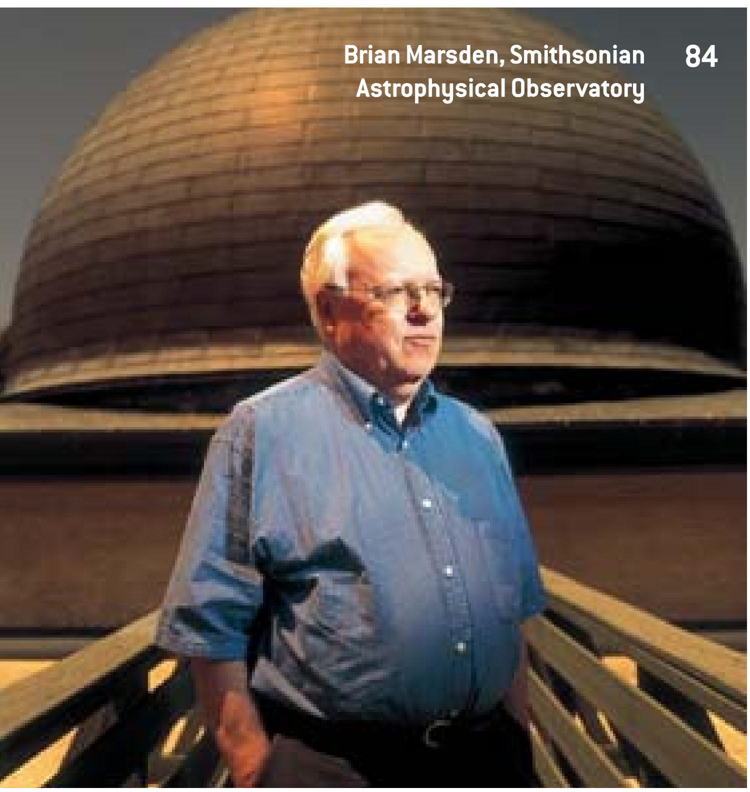

Brian Marsden, Smithsonian Astrophysical Observatory 84

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Cover image by Kenn Brown; photograph by Sanjay Kothari and imaging by Trucollage (*page 5*)

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Houston, You Have a Problem

In retrospect, the missteps that led to the loss of the space shuttle *Columbia* seem so obvious. In every one of the 113 shuttle flights since the program began in 1981, small pieces of insulation foam peeled off the vehicle's external tank during launch and dinged the orbiter. In at least eight flights, larger hunks of foam detached from the bipod ramps (the insulation covering the areas where struts attach the external tank to the orbiter). During the launch of the shuttle *Atlantis* last October, a foot-long chunk fell from a bipod ramp and hit one of the solid-fuel boosters. But in the Flight Readiness Review for the next shuttle mission, NASA managers concluded that the foam strikes did not pose a threat. Instead of thoroughly analyzing the problem, they put out a perfunctory rationale including statements such as "Ramp foam application involves craftsmanship" and "All ramp closeout work was performed by experienced practitioners."

COLUMBIA ASTRONAUTS Kalpana Chawla and Rick Husband shortly before the accident.

One minute and 21 seconds into *Columbia*'s final launch on January 16, a briefcase-size piece of foam separated from the bipod area and slammed into the orbiter's left wing at more than 500 miles an hour. According to the Columbia Accident Investigation Board, which is due to release its report this summer, the impact most likely opened a breach in the wing's leading edge. On February 1, when the the shuttle reentered the atmosphere, superheated gases jetted through the hole like a blowtorch.

Hindsight is 20/20, of course. How could anyone have known that a routine problem that had caused only nicks to the orbiter in 112 flights would do lethal damage in the 113th? But this wasn't the first time that NASA failed to recognize the dangers of a routine anomaly. In several shuttle flights during the mid-1980s, engineers had noticed an ominous sign—partial erosion of the O-rings in the solid-fuel boosters—but nobody heeded their warnings. After an O-ring leak caused the explosion of *Challenger* in 1986, NASA revamped its procedure for launch decisions to involve more engineers and safety experts. Events during the *Columbia* flight, however, showed that the space agency still hadn't learned how to listen to the cautions of its own personnel. When NASA engineers asked the National Imagery and Mapping Agency to take satellite photographs of the shuttle to look for damage from the foam impact, their superiors overruled the request.

To do justice to the seven astronauts killed in the *Columbia* accident, NASA must go far beyond technical fixes to the bipod area. Before the space shuttles are allowed to fly again, the agency must restructure its mission teams so that engineers and safety experts have sufficient resources to fully investigate flight anomalies and enough independent clout to challenge program administrators. In testimony before Congress in May, Harold W. Gehman, Jr., the retired admiral who heads the accident investigation board, observed that NASA engineers cannot persuade the agency to focus on a safety problem unless they have hard data to back up their concerns. Noted Gehman: "The people who would say, 'Wait a minute, this is not safe,' can't come argue their cases with 18 inches worth of documentation, because they aren't funded well enough."

Given the inherent risks of spaceflight and the ungainly design of the shuttle, NASA may not be able to bar a third catastrophe (especially if it keeps the aging shuttles flying until 2015 or longer). But the agency can reduce the chances of another accident in space by improving its communications on the ground.

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NASA-TV *Getty Images*

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On the Web

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FEATURED THIS MONTH

Visit **www.sciam.com/ontheweb** to find these recent additions to the site:

Sci/Tech Web Awards 2003

It's a jungle out there. With more than three billion Web pages to sift through, finding great science sites is harder than ever. The good news is that the editors at *Scientific American* have once again trawled the Internet for the best the Web has to offer. We think our list of winners has something for everyone.

Gecko-Inspired Adhesive Sticks It to Traditional Tape

Move over, Spider-Man—soon the rest of us may be able to scale walls and cling to ceilings, too. Researchers have developed a supersticky adhesive modeled on the gecko foot that grips even the slipperiest surface. So tenacious is this gecko tape, they report, that it could suspend a person from the ceiling by one hand.

Ask the Experts

What causes stuttering?
Speech-language pathologist **Luc F. De Nil** of the University of Toronto explains.

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COURTESY OF ANDRE GEIM

Letters

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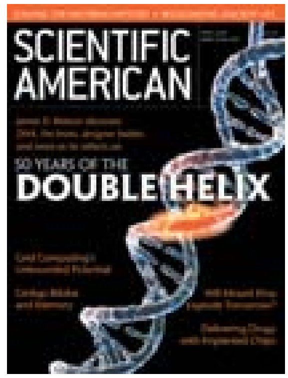
TECHNOLOGY, IT IS OFTEN SAID, is "neutral," neither good nor bad—a tool whose function is determined by the people who control it. Except when it isn't. That was the reaction of several readers to the April editorial "Get Real" [Perspectives]. The editors warned against "technocynics" who may impede the progress of various promising lines of research—including therapeutic cloning and genetically modified foods—based on "abstract worries" about the vague possibility of "doing more harm than good." Some correspondents urged that research should respect differing views on what is damaging, especially regarding precious human life. Critics and defenders of science face off below on this and other topics from the April issue.



REALITY CHECK

"Get Real" [Perspectives] derides opponents of technologies such as cloning as "technocynics," as if they were irrationally antitechnology and antiprogress. Perhaps some are driven by such fears, but many are also dedicated scientists and engineers with solid credentials, successful careers and a deep love for the value of their work. Objecting to how close we are to crossing the line with regard to creating or destroying human life isn't a blanket condemnation of technology.

Who's being hurt in therapeutic cloning? Well, for one, the individual whose life-building stem cells are harvested for use by others. It's tragic irony for you to brush aside warnings about degrading human life, because the callous and flippant attitude expressed in your column reveals that you've already crossed that line of dehumanization in your own hearts, and you seem either not to know or not to care. While we unceasingly pursue answers to the whats and hows of nature and existence, we must remember to keep seeking the whys as well.

Michael Konopik
Menlo Park, Calif.

Your editorial completely ignores a major point that critics make: much science and technological development is funded and controlled by corporations and government—entities that may be concerned with accumulating profits and enhancing power at the expense of ordinary people. The editorial also brushes off the notion that people lack the ability to manage rapid scientific and technological advances. Consider: we are in the midst of an extinction crisis resulting from human population growth and increases in consumption made possible by modern science and technology; the list of Superfund sites is growing; policy to counter global warming remains ineffective.

When Richard Gatling invented the machine gun, he thought it would end war because no one would be foolish enough to charge the weapon, nor would anyone be so inhumane as to actually use it. Many citizens and scientists recognize that nothing is more dangerous to ourselves and the rest of life than hubris.

David M. Johns
McMinnville, Ore.

On the whole, your balanced view of technology seems appropriate. When you suggest that to stop research is to give up trying to make the world a better place, however, you tend to promote your own dangerous extreme. Often technology is used to "fix" something that is really a symptom of a more fundamental systemic dysfunction. Worse, because of the complexities of human and ecological systems, the fixes often have unintended negative consequences. Unfortunately, those problems are usually met, because of the prevalent mind-set, with merely another technofix.

Technology provides useful tools, but it is not the ultimate answer to making the world a better place. For that, we require a paradigm shift into a systems- and complexity-science-based way of thinking.

Mark S. Meritt
Red Hook, N.Y.

Your editorial suggests that those who are wary of genetically modified (GM) foods bemoan all new science and technology. In fact, the opposite is true. GM foods may yet be the solution to the world's hunger problems, but evidence indicates that their genes transfer into other organisms and that the effect on human health may be less than positive. Do we really want weed- or pest-resistance genes in GM crops spreading to native plants? As for human health, the FDA requires extensive testing of new drugs; these molecules, once approved, are administered only to those with a medical need, usually for limited periods and under the watchful eye of a physician. On the other hand, GM foods may be eaten by everyone, unmonitored, for the rest of their life.

Science could address the related questions, and I'd be delighted if the answer came back: "After extensive testing, it has been concluded that GM organisms do not harm humans or the environment on which they depend." But that would take *more* science, not less.

Stephanie Ferguson
Indianapolis

In support of your editorial highlighting some of the illogical and sensationalist views of technocynics, I would like to add more fuel for debate. The association of GM food with Frankensteinian images is irrational. Humans have been eating genetically altered food for hundreds or even thousands of years, since the introduction of agriculture. Although it is possible that food that is genetically modified in certain ways could be deleterious to the health of consumers, such as by the introduction of carcinogens, the mere fact that a food is genetically modified should not be regarded as something alien or harmful. Public education led by scientists is required to avoid the further development of a culture of antiscience and to break down the stigma associated with GM food.

Paul K. Wright
University Hospital of North Durham
Durham, England

HERBAL CAUTION

I just finished "The Lowdown on Ginkgo Biloba," by Paul E. Gold, Larry Cahill and Gary L. Wenk. One thing that was not stressed is that people who take supplements need to inform their health care providers.

Many supplements cause no harm (except perhaps to the pocketbook), and some are beneficial but still may not mix well with conventional medications. An excellent reference is the Natural Medicines Comprehensive Database (www.naturaldatabase.com), a pay site that explains what herbals are used for, what they are safe (or unsafe) for and how they interact with various drugs.

David M. Jones
via e-mail

GINKGO and other herbs may interact with drugs.

FROM *FLORA JAPONICA*, BY SIEBOLD AND ZUCCARINI, LEIDEN 1835/42, IN THE LEIDEN UNIVERSITY BRANCH OF THE NATIONAL HERBARIUM OF THE NETHERLANDS

A GRID'S UTILITY

Ian Foster's article "The Grid: Computing without Bounds" fantastically inflated an interesting software project, Globus, into the certainty of computing as a general utility. Bandwidth is an item the user cannot readily produce, so it is reasonable to make a utility using it. Not so for processing and storage. The computing power of yesteryear's huge mainframes drives today's desktop word processing and games of solitaire. Storage costs $1 a gigabyte. It's not economically sensible to turn things that are essentially free into a utility, as the article proposes.

Which brings me to the second point: bandwidth is not free. Foster provides no discussion of the economic impact of the bandwidth necessary to realize his vision. The price of transporting computer processing and storage cannot compete with the low cost of keeping both local.

In the business world, grid computing is a solution without a problem.

L. L. Williams
Manitou Springs, Colo.

I had difficulty getting excited about grid computing, having experienced the slow, frustrating reality of wide-area distributed networks. The total economic penalty of this inefficiency must be enormous.

Bruce Varley
Melville, Western Australia

ERRATA The News Scan story "Ma's Eyes, Not Her Ways," by Carol Ezzell, should have noted that the cloned pigs were created at Texas A&M University by Shawn Walker and Jorge A. Piedrahita (now at North Carolina State University) and that they initiated the collaboration with Ted Friend and Greg Archer of Texas A&M, which resulted in the observation that clones have differing physical and behavioral attributes. Cloned pig siblings in the study had varying numbers of teats, not teeth, as stated in the article.

Simulations in a pressure chamber that mimics conditions on the sunken oil tanker *Prestige* achieved about 350 atmospheres, not 100 ["Oiling Up Spain," by Luis Miguel Ariza, News Scan].

Ray Davis was a scientist in the chemistry department at Brookhaven National Laboratory when he did his pioneering work that began the field of solar neutrino research ["Solving the Solar Neutrino Problem," by Arthur B. McDonald, Joshua R. Klein and David L. Wark].

50, 100 & 150 Years Ago
FROM SCIENTIFIC AMERICAN

Fixing Dirt ▪ Atomic Revision ▪ Epidemic News

AUGUST 1953

CONTRACEPTION—"Research on contraception by physiological rather than mechanical methods is making considerable progress, according to a recent report in *Science* by Paul Henshaw of the Planned Parenthood Foundation. The studies have two objectives: to improve the fertility of childless couples, and to develop a reliable and convenient form of contraception by pill, injection, timing or a combination of these methods."

BETTER SOIL... MAYBE—"Some hail the new soil conditioners as wonder chemicals which, sprinkled on the ground, turn clay or sand to rich, loose topsoil in a few hours, removing all need for organic matter and the back-breaking labor of digging and cultivating. Chemically they are long-chain polymers. Functionally their molecular charges attract clay particles in the soil like a magnet, forming many small lumps or aggregates. The Connecticut Agricultural Experiment Station ran some tests and it was found that if the chemicals are put down in excessive amounts, they retard germination and repress plant growth. Being essentially plastics, the conditioners literally plasticized the soil. However, some tests have shown increased yields."

AUGUST 1903

E.T. ISN'T PHONING—"On Mars, when the planet comes into favorable position for observation, astronomers are able to see one or more irregular bright projections on the sunrise or sunset line. The nature of these projections is pretty well understood by astronomers, but the biennial press reports of such sightings give rise to a question on the part of the public as to whether they could be signals from intelligent beings on that planet. All the observed phenomena can be satisfactorily accounted for on the theory that the projections are due to clouds of considerable size, at great elevations in the rarefied atmosphere. Such clouds would be illuminated by the sun's rays while the land areas beneath them were still so dark as to form a black background. —W. W. Campbell, Director, Lick Observatory"

316 MILLION ELECTRIC CANDLES—for lighthouses, 1903

THE NEW CHEMISTRY—"Just what shall be done with the newly discovered radioactive substances is a problem that perplexes every thinking physicist. They refuse to fit into our established and harmonious chemical system; they even threaten to undermine the venerable atomic theory, which we have accepted unquestioned for well-nigh a century. The elements, once conceived to be simple forms of primordial matter, are boldly proclaimed to be minute astronomical systems of whirling units of matter. This seems more like scientific moonshine than sober thought; and yet the new doctrines are accepted by Sir Oliver Lodge and by Lord Kelvin himself."

ELECTRICITY FOR LIGHT—"Our illustration shows a searchlight made by the firm of Schuckert & Co., in Nuremberg, Germany, with an Iris shutter, half closed, which has a diameter of 6 feet 6 inches and throws a beam of light of 316 million candle power. Searchlights such as this are destined to replace the old petroleum lights that so long flashed out their danger signals to mariners from lighthouses."

AUGUST 1853

WEATHER BALLOONIST—"Mr. John Wise, the celebrated aerial navigator of nearly two hundred atmospheric voyages, writes to us: 'In your article on the subject of Thunder and Lightning you say you "have come to the conclusion that for one vertical flash of lightning that reaches the earth, fifty are horizontal—dissipating in the atmosphere like the fibres of a vine spreading out from the main trunk." I think you are correct in your conclusion; the dissipation takes place in the lower cloud surface. I have witnessed the same thing when sailing above the layer of clouds during thunder storms.'"

PESTILENCE AT HOME—"The city of New Orleans is severely afflicted with yellow fever this summer. No less than 200 have died in one day."

PESTILENCE ABROAD—"The cholera is now raging fearfully in some places of Denmark. In Copenhagen, 300 died of it in one day."

news SCAN

CLIMATE CHANGE

Hot Words

A CLAIM OF NONHUMAN-INDUCED GLOBAL WARMING SPARKS DEBATE **BY DAVID APPELL**

In a contretemps indicative of the political struggle over global climate change, a recent study suggested that humans may not be warming the earth. Greenhouse skeptics, pro-industry groups and political conservatives have seized on the results, proclaiming that the science of climate change is inconclusive and that agreements such as the Kyoto Protocol, which set limits on the output of industrial heat-trapping gases, are unnecessary. But mainstream climatologists, as represented by the Intergovernmental Panel on Climate Change (IPCC), are perturbed that the report has received so much attention; they say the study's conclusions are scientifically dubious and colored by politics.

TREE RINGS hold clues about past climate, because temperature affects a tree's growth.

DAVID BROOKOVER *Photonica*

Sallie Baliunas and Willie Soon of the Harvard-Smithsonian Center for Astrophysics reviewed more than 200 studies that examined climate "proxy" records—data from such phenomena as the growth of tree rings or coral, which are sensitive to climatic conditions. They concluded in the January *Climate Research* that "across the world, many records reveal that the 20th century is probably not the warmest nor a uniquely extreme climate period of the last millennium." They said that two extreme climate periods—the Medieval Warming Period between 800 and 1300 and the Little Ice Age of 1300 to 1900—occurred worldwide, at a time before industrial emissions of greenhouse gases became abundant. (A longer version subsequently appeared in the May *Energy and Environment*.)

In contrast, the consensus view among paleoclimatologists is that the Medieval Warming Period was regional, that the worldwide nature of the Little Ice Age is open to question and that the late 20th century saw the most extreme global average temperatures.

Scientists skeptical of human-induced warming applaud the analysis by Soon and Baliunas. "It has been painstaking and meticulous," says William Kininmonth, a meteorological consultant in Kew, Australia, and former head of the Australian National Climate Center. But he says that "from a purely statistical viewpoint, the work can be criticized."

And that criticism, from many scientists who feel that Soon and Baliunas produced deeply flawed work, has been unusually strident. "The fact that it has received any attention at all is a result, again in my view, of its utility to those groups who want the global warming issue to just go away," comments Tim Barnett, a marine physicist at the Scripps Institution of Oceanography, whose work Soon and Baliunas refer to. Similar sentiments came from Malcolm Hughes of the Laboratory of Tree-Ring Research at the University of Arizona, whose work is also discussed: "The Soon et al. paper is so fundamentally misconceived and contains so many egregious errors that it would take weeks to list and explain them all."

Rather than seeing global anomalies, many paleoclimatologists subscribe to the conclusions of Phil Jones of the University of East Anglia, Michael Mann of the University of Virginia and their colleagues, who began in 1998 to quantitatively splice together the proxy records. They have concluded that the global average temperature over the past 1,000 years has been relatively stable until the 20th century. "Nothing in the paper undermines in any way the conclusion of earlier studies that the average temperature of the *late* twentieth century in the Northern Hemisphere was anomalous against the background of the past millennium," wrote Mann and Princeton University's Michael Oppenheimer in a privately circulated statement.

The most significant criticism is that Soon and Baliunas do not present their data quantitatively—instead they merely categorize the work of others primarily into one of two sets: either supporting or not supporting their particular definitions of a Medieval Warming Period or Little Ice Age. "I was stating outright that I'm not able to give too many quantitative details, especially in terms of aggregating all the results," Soon says.

Specifically, they define a "climatic anomaly" as a period of 50 or more years of wetness or dryness or sustained warmth (or, for the Little Ice Age, coolness). The problem is that under this broad definition a wet or dry spell would indicate a climatic anomaly even if the temperature remained perfectly constant. Soon and Baliunas are "mindful" that the Medieval Warming Period and the Little Ice Age should be defined by temperature, but "we emphasize that great bias would result if those thermal anomalies were to be dissociated" from other climatic conditions. (Asked to define "wetness" and "dryness," Soon and Baliunas say only that they "referred to the standard usage in English.")

What is more, their results were nonsynchronous: "Their analysis doesn't consider whether the warm/cold periods occurred at the same time," says Peter Stott, a climate scientist at the U.K.'s Hadley Center for Climate Prediction and Research in Bracknell. For example, if a proxy record indicated that a drier condition existed in one part of the world from 800 to 850, it would be counted as equal evidence for a Medieval Warming Period as a different proxy record that showed wetter conditions in another part of the world from 1250 to 1300. Regional conditions do not necessarily mirror the global average, Stott notes: "Iceland and Greenland had their warmest periods in the 1930s, whereas the warmest for the globe was the 1990s."

Soon and Baliunas also take issue with the IPCC by contending that the 20th century saw no unique patterns: they found few climatic anomalies in the proxy records. But they looked for 50-year-long anomalies; the last century's warming, the IPCC concludes, occurred in two periods of about 30 years each (with cooling in between). The warmest period occurred in the *late* 20th century—too short to meet Soon and Baliunas's selected requirement. The two researchers also discount thermometer readings and "give great weight to the paleo data for which the uncertainties are much greater," Stott says.

The conclusion of Soon and Baliunas that

CORAL can serve as climate proxy records: their chemical makeup depends on temperature and salinity.

RANDY OLSON *Aurora*

POLITICS IN PEER REVIEW?

Mainstream climatologists perceive flaws in a paper by Willie Soon and Sallie Baliunas, the two Harvard-Smithsonian researchers who produced results skeptical of human-induced global warming. Some conclude that politics drove the paper's publication in *Climate Research*. One of the journal's editors, Chris de Freitas of the University of Auckland, has frequently editorialized in the New Zealand press against the overwhelmingly accepted conclusions of the IPCC. And at least three scientists who were on the journal's peer-review panel—Wolfgang Cramer, Tom Wigley and Danny Harvey—have complained that de Freitas has published papers they have deemed unacceptable without notifying them.

Wigley says that such action is very unusual; de Freitas responds that he "was not too concerned [about Wigley's complaint] as periodically I receive diametrically opposed assessments from experts," especially, he says, "as the work in question was a critical assessment of Wigley's own work."

The Soon and Baliunas paper produced political results in one respect: it seems to have emboldened the Bush administration to edit a June Environmental Protection Agency report so that it no longer represented a scientific consensus about climate change. The *New York Times* reported that, as a result, the EPA decided to publish much weaker statements about global warming.

the warming during the 20th century is not unusual has engendered sharp debate and intense reactions on both sides—Soon and Baliunas responded primarily via e-mail and refused follow-up questions. The charges illustrate the polarized nature of the climate change debate in the U.S. "You'd be challenged, I'd bet, to find someone who supports the Kyoto Protocol and also thinks that this paper is good science, or someone who thinks that the paper is bad science and is opposed to Kyoto," predicts Roger Pielke, Jr., of the University of Colorado. Expect more of such flares as the stakes—and the world's temperatures—continue to rise.

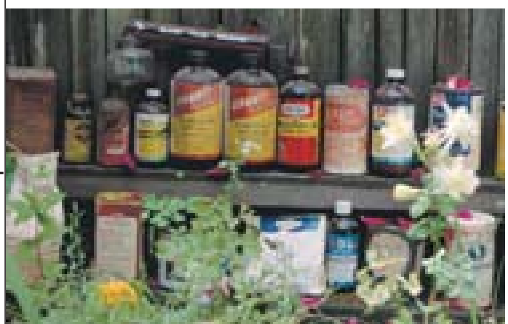
David Appell is based in Lee, N.H.

HEALTH

Secret Ingredients

"INERT" COMPOUNDS MAY BE CHEMICALLY ACTIVE—AND TOXIC **BY DAVID J. EPSTEIN**

Spraying for mosquitoes has increasingly become a summer routine in many areas, thanks to the West Nile virus. Residents who want to find out what's being sprayed could turn to the product label on the container. But even a thorough reading of the label won't tell the whole story. Most "inert" ingredients, which often constitute up to 99 percent of the product contents, are not listed. Yet they can be biochemically active—for example, an unlisted ingredient in the mosquito pesticide Dibrom is naphthalene, which might cause cancer and developmental problems in exposed children. Now some activists are trying to get the Environmental Protection Agency to force chemical makers into revealing their hidden compounds.



PESTICIDE LABELS do not list the "inert" ingredients.

GALEN ROWELL *Corbis*

According to the Federal Insecticide, Fungicide and Rodenticide Act, pesticide ingredients qualify as inert when their function in a product is something other than killing the target pest. For instance, an inert may make a product sticky, or sprayable, or attractive to a particular kind of bug or rodent. Yet the term "inert" does not bear on the toxicity of the ingredient to other organisms.

In the case of Monsanto's product Roundup, currently the most used herbicide in the world, a Texas Tech University study published in 2000 revealed a 90 percent decrease in the production of certain reproductive hormones in exposed mice. After the researchers gave mice glyphosate, the only listed active ingredient in Roundup, they did not see the decrease in hormone production. They concluded that the inert ingredients in the product caused the reduced sexual hormones.

In March 2000 the EPA brought together public-interest groups and pesticide manufacturers for a workshop to discuss ways to enhance disclosure of inert ingredients to consumers and to emergency health professionals, who can be ill equipped to treat exposure symptoms if they cannot identify the culprit chemical. Since 1987, pesticide manufacturers have had to register all their ingredients with the EPA, but most inerts are protected from public disclosure as trade secrets. The EPA initiative categorized the compounds into four lists and pushed for further toxicity testing.

More than half of all EPA-registered inerts fall into List 3: "inerts of unknown toxicity." And according to a survey by the Northwest Coalition for Alternatives to Pesticides (NCAP) in Eugene, Ore., about a quarter of inert substances, many on List 3, are already classified as hazardous under the Clean Air Act, the Safe Drinking Water Act and other federal statutes.

Industry representatives argue that full disclosure of inerts would cause manufacturers severe competitive harm. "It basically would tear down the art we've practiced and

AN END TO A BUG'S LIFE

Pesticides contain many kinds of chemicals labeled as inert. The EPA places them into four categories; a few examples are listed (see www.epa.gov/opprd001/inerts/lists.html).

List 1 ("of toxicological concern"; 7 compounds): Phenol, hydroquinone

List 2 ("potentially toxic"; 95 compounds): Diesel fuel, nitromethane, certain petroleum distillates, toluene

List 3 ("of unknown toxicity"; about 2,000 compounds): Asphalt, atropine, borax, coal tar, dried blood, formaldehyde, hydrogen peroxide, kerosene, naphthalene, propane, shellac, sulfuric acid, turpentine, tobacco dust

List 4 ("of minimal concern"; more than 1,000 compounds): Beer, egg white, oyster shells, paprika, polyurethane, sperm whale oil, sugar, sulfur, yeast just give it to our competitors globally who can produce it at lower costs because of cheaper labor and lower safety standards," comments Chip Collins of Stepan, a firm based in Northfield, Ill., that makes inerts for a variety of products, including pesticides.

NCAP and other public-interest representatives maintain that the means to reverse-engineer pesticide formulations, which they argue is available to companies with well-equipped labs, already renders inert identities reasonably obtainable to competitors. Data about the inerts should therefore be subject to Freedom of Information Act requests. In fact, through such requests NCAP has obtained documentation from the EPA on inerts in hundreds of products, but some requests "have been in the hopper since 1996," NCAP's Caroline Cox says. Moreover, manufacturers retain the ability to deny disclosure if they claim that they will suffer competitive harm.

During the workshop the EPA formally denied a petition by NCAP to mandate disclosure of all inert ingredients on pesticide labels. Yet earlier this year the EPA began a pilot program of "voluntary disclosure" to urge companies to offer up more ingredient information to doctors and toxicologists, notes Cameo Smoot of the EPA Office of Pesticide Programs. Still, Cox is skeptical of the success of voluntary programs. "Voluntary disclosure is the status quo, so what's the difference?" she asks.

So now NCAP has gone to court to force EPA officials to recognize the petition for full disclosure. "My personal opinion is that they will not take action unless essentially they have to," Cox adds. "The briefs have all been filed," she says, "but we currently have no idea what the judge will rule." Pesticide inerts could be destined to remain a public mystery.

David J. Epstein is based in New York City.

LABELS WITH LESS

List 1 inerts are now required on product labels. One positive effect of this rule, according to the Environmental Protection Bureau at the New York State Attorney General's office, is that several manufacturers decided to drop certain inerts altogether rather than subject them to the rigorous testing required to determine their degree of toxicity.

ORIGINS

Sourcing Sapiens

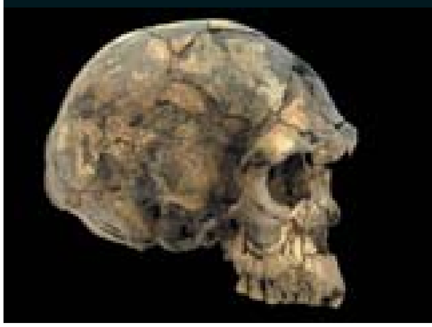
NEW FOSSILS AND DNA TESTS GET TO THE ROOTS OF OUR SPECIES BY KATE WONG

For more than a century, paleoanthropologists have been at loggerheads over the origin of modern humans. Two factions occupy the forefront of the debate: those who subscribe to the Out of Africa theory, which holds that *Homo sapiens* arose in Africa alone between 200,000 and 150,000 years ago and subsequently spread across the globe, replacing archaic hominids; and those who espouse the multiregional evolution theory, which proposes that modern humans emerged from archaic populations across the Old World.

The Out of Africa model has come out as the clear favorite, bolstered by numerous genetic studies. Critics, however, have charged that fossil support for the theory is flimsy. If Africa was the fountainhead of modern human morphology, then the first modern-looking fossils should come from that continent. But a hole in the African fossil record between 300,000 and 100,000 years ago, when the transition to morphological modernity is believed to have occurred, has prevented scientists from testing that prediction.

New finds from a site called Herto in Ethiopia's Middle Awash region bridge that gap. In the June 12 *Nature,* Tim D. White of the University of California at Berkeley and his colleagues describe three skulls reliably dated at nearly 160,000 years old that they say represent the earliest near-modern humans on record. The fossils, assigned to a new subspecies, *H. sapiens idaltu,* exhibit such modern traits as a globular braincase, but they also retain some ancient features—a heavy browridge, for example. Their anatomy and antiquity, the researchers observe, link earlier archaic African forms to later fully modern ones, thereby providing strong evidence that Africa was the birthplace of our kind.

The Herto hominids also bear on another, related question: Namely, were Neandertals among the forebears of living peoples? Whereas Out of Africa theorists contend that such archaic hominids did not contribute sig-



ALMOST MODERN: 160,000-year-old skull from Ethiopia suggests that our species stemmed from Africa (*top*). An artist's reconstruction shows what the individual might have looked like in life (*bottom*).

© 2001 DAVID L. BRILL *Brill Atlanta* (*top*); JAY MATTERNES (*bottom*)

NEED TO KNOW: NEANDERTAL DNA

The Neandertal mitochondrial DNA (mtDNA) sequences published so far have been found to differ considerably from those of contemporary Europeans, thus supporting the Out of Africa proponents' view that Neandertals did not contribute to the modern gene pool. But some anthropologists complain that to ensure that the sequences truly come from Neandertals and not modern contaminants, molecular biologists typically accept as valid only those sequences that lie outside of the modern human range. This requirement thereby stacks the deck against Neandertals that might have DNA like ours, which is what those advocating the multiregional evolution theory expect to see.

nificantly to the modern human gene pool, some multiregionalists have argued that the Neandertals independently evolved into modern Europeans. The presence of near moderns in Africa while the Neandertals were still developing their distinctive characteristics in Europe makes it highly unlikely that Neandertals were ancestral to modern humans, White's team asserts.

Scientists working on ancient DNA have reached similar conclusions. In May, Giorgio Bertorelle of the University of Ferrara in Italy and his colleagues reported that mitochondrial DNA (mtDNA) sequences from two early modern European fossils differ markedly from the mtDNA sequences previously recovered from four Neandertal specimens. They fall within the range of genetic variation seen in Europeans today, however.

Not everyone is convinced by the case against Neandertal ancestry. Fred H. Smith of Loyola University of Chicago counters that although the Herto finds add weight to the idea that modern humans originated in Africa, they do not address the question of whether those moderns mingled with the archaic hominids they encountered on leaving their homeland. Smith has argued that a number of early modern European fossils possess Neandertal traits, suggesting that the two groups interbred. Neither is Smith persuaded by the DNA data. "Two individuals do not tell us what the genetic makeup of early modern human populations was," he remarks. "We need a good deal more data to determine whether Neandertals contributed genetically to that population."

Although disagreement over the origin of modern humans and the fate of the Neandertals and other ancient hominids persists, the dispute itself has evolved. "Continuity versus replacement is dead," declares Erik Trinkaus of Washington University. The debate now is over "trivial amounts of admixture versus major amounts of admixture." For his part, Trinkaus suspects that early modern humans and Neandertals paid little attention to the physical differences between them. "They saw each other as people," he surmises—and did what people do.

GEOPHYSICS

Deep Thoughts

HOW TO JOURNEY TO THE CENTER OF THE EARTH—MAYBE **BY SARAH SIMPSON**

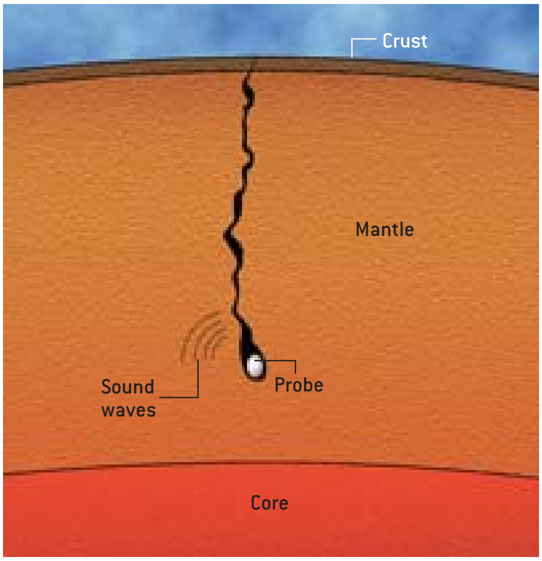
P**our a few million tons** of molten iron into a modest crack in the planet's surface, and the seething blob will burrow some 3,000 kilometers down to the outer core in a matter of weeks. Plant a grapefruit-size probe inside the sinking metal, and you have a sensational new way to explore the earth's inner workings.

At least that's how David J. Stevenson, a planetary scientist at the California Institute of Technology, envisions it. Some of Stevenson's colleagues have laughed out loud at his musings; others have called them "goofy." But at least a few geophysicists admit that the idea is promising, even feasible.

"We don't know that it *wouldn't* work," says earth scientist Paul J. Tackley of the University of California at Los Angeles. And he sees plenty of reasons to launch such a journey.

What scientists currently know about the inner earth has been inferred indirectly—from the way earthquake vibrations travel through the planet's middle or from altered bits of mantle rocks that are coughed up the throats of volcanoes. Most researchers have abandoned any hope of making direct observations: drilling below about 12 kilometers has proved futile because of the intense pressures exerted by the overlying rock.

What makes Stevenson's plan different is that it requires no drilling. Instead the probe's journey begins with a crack, which would require the equivalent of a few megatons of TNT to create. Once filled with 100,000 to 10 million metric tons of iron, the crack would grow downward. The sinking iron, with a density about twice that of the surrounding rock, would advance the crack because of the force of gravity—like an ax splitting a log. Pressure of up to about 135 gigapascals—or 20 million pounds per square inch—within the mantle would reseal the crack above.



GOING DOWN: A few million tons of molten iron would envelop a small probe. As the molten mass sank toward the core, the probe would relay temperature and composition readings to the surface via sound vibrations. (Diagram not to scale.)

NINA FINKEL; SOURCE: CALIFORNIA INSTITUTE OF TECHNOLOGY

Controlling the shape of the crack would be more difficult, Tackley cautions. Natural fractures might divert some of the iron from its intended path. Tackley and Paul Johnson, a geophysicist at the University of Washington, also point out that at least some of the iron would freeze as it descended through the relatively cold environs of the deep crust.

Overcoming the engineering difficulties may require melting much more iron than would ever be reasonable, Stevenson concedes. Even more uncertain, he says, are the time and money required to invent a probe that could survive the tortures of the trip (perhaps with electronics crafted from diamonds) while successfully communicating its findings (probably via low-intensity sound waves) to researchers above.

"I suspect the actual cost of a project of this sort would make even NASA blush," Johnson speculates. But he adds that while it's easy to be a naysayer about any of a dozen aspects of this plan (cracking the earth's crust would probably require nuclear explosions) the proposal's greatest value is getting people to talk in new ways about a scientific dream long since rejected by most.

Stevenson admits that although the ideas had been bouncing around in his head for a decade, it took him only six hours to write them up—spurred on in part by Paramount Pictures's recent release of its geophysical thriller, *The Core*.

Though not passionately committed to realizing his scheme, Stevenson hopes that his fellow scientists will see his proposal's serious side. In the past 40 years, NASA has spent more than $10 billion on unmanned exploration of space. Stevenson thinks our home planet is worth a comparable investment—a rather audacious message coming from someone whose successful, 30-year career has been financed largely by NASA.

"Knowing the composition and temperature of the mantle and core is fundamental to understanding the origin of the earth," he says. "We will never know if we don't go there."

SIDE EFFECTS AND CORE CONCERNS

Sending a blob of molten iron deep inside the earth has spawned a few thought experiments, if nothing else. Burning enough fossil fuel to melt the iron would surely exacerbate global warming, says Paul Johnson of the University of Washington. To liquefy 10 million metric tons of iron, a blast furnace would emit about a megaton of carbon dioxide—a small but significant percentage of the annual production of the greenhouse gas worldwide. But if the plan really works, "it could be the antidote to global warming," Johnson muses. Riding to the core inside molten metal could be the long-elusive answer for how to dispose safely of spent nuclear reactor rods, making the switch from coal-burning to nuclear power plants more desirable.

PHYSICS

View from VIRGO

A NEW GRAVITY OBSERVATORY COMES ONLINE **BY ALEXANDER HELLEMANS**

High on any astrophysicist's wish list is the detection of gravitational waves, ripples of spacetime caused by such violent phenomena as supernova and merging black holes. Researchers are pinning their hopes on kilometer-long detectors. The world's biggest, the $371-million Laser Interferometer Gravitational Observatory (LIGO), began taking data last year. This past July a French-Italian collaboration inaugurated VIRGO, which, though second fiddle in size to LIGO, may be in a better position to register the tiny, elusive wrinkles. And costing about 75 million euros (roughly $87 million), it is substantially cheaper.

Like LIGO, VIRGO is a so-called Michelson interferometer: light from a laser passes a beam splitter and travels down two perpendicular evacuated pipes. The beams are reflected back by mirrors at the end of the pipes and "interfere" with each other. Specifically, they recombine destructively—that is, the waves cancel each other out. Any slight change in arrival time (phase) gives itself away as a faint beam that can be detected by an optical sensor.

The LIGO interferometer arms are four kilometers long; VIRGO's arms extend three kilometers. Both are effectively much longer because the beams bounce back and forth dozens of times. Over these distances, the distortions of space are approximately a billionth the size of an atom—sufficient to cause noticeable differences in the phase of the combining light beams. The challenge so far has been boosting the detectors' sensitivity: vibrations in the mirrors can obscure the tiny signals.

Seismicity is a major problem for LIGO [see "Ripples in Spacetime," by W. Wayt Gibbs; Scientific American, April 2002]. It limits the detection of signals below 60 hertz, where astrophysicists have more confidence in what a gravitational signal should look like and where the strongest signals are expected to be.

VIRGO includes seismic isolators for every optical component in the interferometer. Each "superattenuator" comprises six sets of coupled springs and weights housed in a 10-meter-tall tower. The weights act like pendulums, damping horizontal swaying, and the combinations of springs and weights curtail vertical movements. The attenuators tame seismic motions by a factor of 10^{-12}, reports VIRGO spokesperson Adalbert Giazotto of the National Institute for Nuclear Physics in Italy, one of the research groups participating in VIRGO. That attenuation enables the detector to reach its cutoff frequency of 10 hertz.

A second problem is thermal noise, especially that caused by the laser beam itself: the laser spots hit the center of the mirrors, heating them unevenly and thereby deforming them. In anticipation of future upgrades that would boost beam strength (and detection sensitivity), VIRGO designers want to incorporate cryogenic coolers, although excessive cooling will add mechanical noise at low frequencies, says physicist Flavio Vetrano of the University of Urbino, Italy's spokesperson for VIRGO.

LIGO wants to introduce seismic isolation and thermal control (whereby the mirrors are not cooled but heated on the periphery to compensate for the heating at their centers). These improvements are planned for the next-generation LIGO detectors, which should be implemented around 2006, according to Lee Samuel Finn, who directs the Center for Gravitational Wave Physics at Pennsylvania State University.

EUROPEAN GRAVITATIONAL OBSERVATORY

VIRGO INTERFEROMETER is built on a layer of sediment in the alluvial plain of the Arno River in Cascina near Pisa, Italy. VIRGO's designers chose this site because of its low level of microseismicity.

Finn expects that merging massive black holes will be the first objects to have their gravitational waves detected. But because sources of gravitational radiation are poor emitters of light, astronomers may have missed still unknown classes of objects. "The first thing we might see may be something unanticipated. I am optimistic in that regard," Finn remarks.

VIRGO joins a growing family of smaller gravitational-wave detectors sprouting around the globe, such as GEO in Germany and TAMA in Japan. A simultaneous detection of an unexpected signal by the world's interferometers would be crucial to proving the existence of gravitational waves. Although contacts among the observatories right now are largely informal, Vetrano looks forward to a time when they will function as a single machine.

Alexander Hellemans is a writer based in Naples, Italy.

PICKING A PATTERN

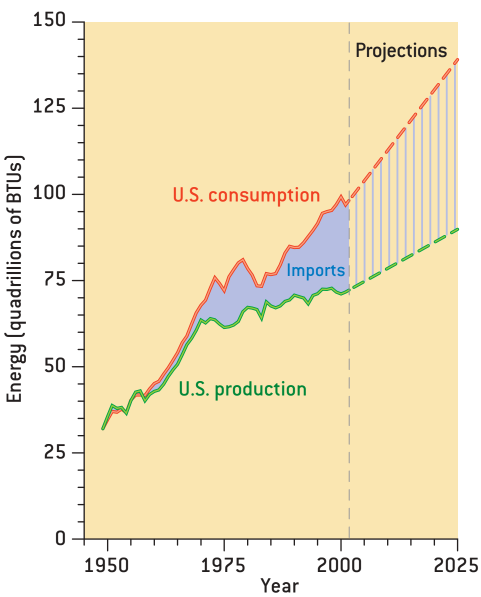
Gravitational-wave signals will be buried deeply in noise, so scientists will have to know what to look for. They will compare their interferometer signals with so-called templates, or gravitational-wave patterns. These templates come from models of binary black holes or neutron stars spiraling toward a collision course. Therefore, detecting a signal depends to a large extent on the correctness of these models. Unfortunately, the parameters, such as velocities, spins and masses of the objects, vary widely, remarks Flavio Vetrano, Italy's spokesperson for VIRGO: "We are facing a catch-22: for recognizing a signal we should have good templates, but for having good templates we need a true signal."

Energy Crunch

AVOIDING FUTURE SHORTAGES DEMANDS CRUCIAL CHOICES NOW **BY RODGER DOYLE**

Summer now often means rolling blackouts and brownouts—on top of rising utility bills and higher prices at the pumps. Unpredictable circumstances can lead to energy headaches—hot weather partly caused California's infamous shortages of 2001—but the main culprit is inadequate investment and lack of an integrated power grid to transmit electricity from one area to another during emergencies.

The chart shows an increasing gap between consumption and domestic production, one that historically has been filled by importing fuels, mostly oil and natural gas. The growing dependence on imports puts the U.S. at risk, not only because 53 percent of the world's proven oil reserves are in the volatile Persian Gulf region but because pipelines and international sea lanes must be protected. Additionally, the growing need for imports contributes to the economic vulnerability of the U.S. by increasing the foreign trade debt [see By the Numbers, February 2000]. And of course, fossil-fuel consumption produces carbon dioxide and other heat-trapping gases, thereby contributing to global warming.



SOURCE: U.S. Department of Energy, Energy Information Administration. Projections are based on the EIA "Reference case" (www.eia.doe.gov).

An endless supply of clean energy—say, from nuclear fusion plants or orbiting solar panels beaming down microwave energy—may someday be possible. But such radical technology will not be available soon. To address America's needs in the next 25 to 50 years, the Bush administration detailed a controversial plan in 2001, favored by industry, called the *National Energy Policy.* It calls for, among other measures, investing huge sums in the oil, gas, electricity and coal infrastructures, opening the Arctic National Wildlife Refuge in Alaska to oil and gas development, expanding the use of nuclear (fission) power, and developing a national power-grid system to prevent local and regional electricity shortages.

Among the more prominent counterplans is the *Clean Energy Blueprint,* issued by a consortium that includes the Union of Concerned Scientists (UCS). This strategy calls for considerably less investment in fossil-fuel infrastructure and greater investment in renewable energy. Of all such sources—solar, geothermal and biomass—wind power emerges as the most important to the UCS, which considers it essential to any plan to meet U.S. energy needs over the next two decades. The UCS estimates that in the 20th year of implementation, the proposed measures will reduce annual energy consumption by 20 percent as compared with the "business as usual" forecast of the U.S. Energy Information Administration that underlies the administration proposal.

This past June, U.S. Secretary of Energy Spencer Abraham warned that the country is critically low on natural gas. Whether this news will nudge the U.S. into making the really big decisions about energy policy is unclear. Few Americans feel that there is an energy crisis, to judge by Gallup polls, which consistently show that "lack of energy" or "energy crisis" is at the bottom of their list of important problems facing the nation.

Rodger Doyle can be reached at rdoyle2@adelphia.net

FURTHER READING

National Energy Policy: Report of the National Energy Policy Development Group. May 2001. Available through the Office of the President of the United States (www.whitehouse.gov/energy).

Clean Energy Blueprint: A Smarter National Energy Policy for Today and the Future. Steven Clemmer et al. Union of Concerned Scientists with the American Council for an Energy-Efficient Economy, and the Tellus Institute, October 2001 (www.ucsusa.org).

Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet. Martin I. Hoffert et al. in *Science,* Vol. 298, pages 981–987; November 1, 2002.

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Annual Energy Outlook 2003 with Projections to 2025. Energy Information Administration, January 2003 (www.eia.doe.gov).

RODGER DOYLE

ENTOMOLOGY

Buzz Off, Heat

Hornets may chill out with a bit of electricity, say a group of biologists and physicists from Tel Aviv University. Infrared images of hornets anesthetized in their nest revealed that the cuticle around body parts such as the abdomen could be up to 3 degrees Celsius cooler than the nest material. Evaporation from the mouth cannot account for the abdominal cooling; rather the researchers assert that the hornets' cuticles may be thermoelectric. Such materials change temperature when an electric current passes through them. But insect physiologist Allen Gibbs of the University of Arizona thinks that evaporative cooling could in fact do the trick and that the measurements may be misleading because of differences in air and nest temperature. Until studies of the cuticle's thermal and electrical conductivity and the hornets' water loss and metabolic activity come in, he says, "put me down as a skeptic." The paper scorches the pages of the May 30 *Physical Review Letters*.

—JR Minkel

ORIENTAL HORNETS (*Vespa orientalis*), shown here munching raw meat, may stay cool with electricity.

ENVIRONMENT

Not So Friendly Hydrogen

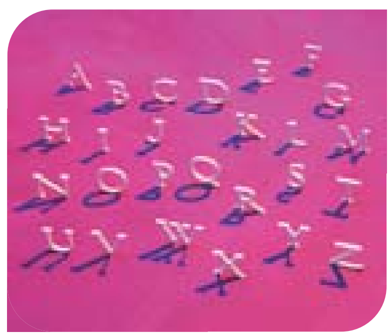
Burning oil and gas can lead to smog, acid rain and global warming, whereas burned hydrogen generates only water. But hydrogen engines may not prove as environmentally friendly as thought. Current systems are leaky, with 10 percent or more of hydrogen escaping uncombusted. California Institute of Technology researchers calculate that if hydrogen fuel cells replaced all oil- and gas-burning technologies, people would release four to eight times more hydrogen into the atmosphere than they do now. The hydrogen would oxidize and form water, clouding the overlying stratosphere, and the resulting cooling would encourage ozone-destroying chemical reactions. The investigators say that preventing hydrogen seepage could offset this damage, as could decreases in ozone-eating chlorofluorocarbons over time and better-than-expected hydrogen absorption by soil. Their report appears in the June 13 *Science*. *—Charles Choi*

VISUAL RECOGNITION

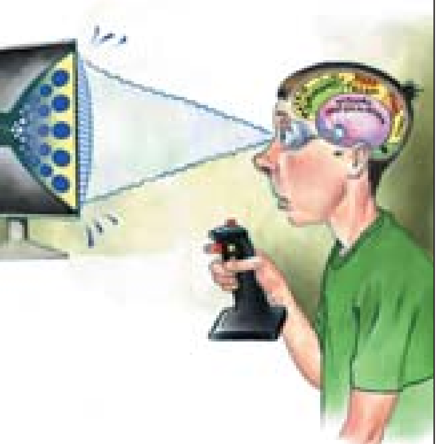
If U Cn Rd Ths . . .

Despite having read 100 million words or more by age 25, the average literate person does not have an easier time identifying common words compared with any word of the same length. Researchers asked volunteers to make out familiar English words or letters hidden in various levels of contrast. Reading efficiency was linked not to how common a word was but to how many letters it had: four-letter words were twice as hard to recognize as two-letter ones, for instance. Furthermore, words proved unreadable unless tiny features of each letter are recognizable, demonstrating severe limitations on the brain's ability to process visual patterns, the researchers say. Such handicaps may have arisen to suppress reflexive attempts to recognize a deluge of inconsequential details. The findings appear in the June 12 *Nature*.

—Charles Choi



FEATURES on letters help enable reading.



DATA POINTS: TRIGGER HAPPY

Fans of shoot-'em-up video games process visual information better than nongamers. C. Shawn Green and Daphne Bavelier of the University of Rochester tested subjects on various tasks, such as recognizing an object in a sequence and counting several items at once. Practice with action games enabled nonplayers to improve their visual attention skills—useful perhaps in driving and in combat training.

Number of items flashed that game players could see: 4.9

Number that nongame players could see: 3.3

Accuracy of game players: 78

Accuracy of nongame players: 65

Increase in flashed items seen among those trained on action game Medal of Honor: 1.7

Increase in those trained on puzzle game Tetris: 0

Daily training time: 1 hour

Number of training days: 10

KRIS MERCER (*top*); PETE McARTHUR (*bottom*); ILLUSTRATION BY MATT COLLINS

ECOLOGY

Fueling Predictions

BETTER FORECASTS may prevent blazes such as this one last year in California's Anza-Borrego Desert State Park.

Wildfire predictions rely heavily on summer weather forecasts, alerting fire crews only a few weeks in advance. But warnings might be extended by a year or more, because long-term climate can have an even greater influence than short-term weather. Anthony L. Westerling of the Scripps Institution of Oceanography and his colleagues correlated more than 20 years of climate and vegetation records with wildfire statistics. Their analysis reveals that the flammability of nonforested regions—home to more than half of U.S. wildfires—depends most on rainfall during previous summers. If persistent drought kills off grasses and shrubs, then the next year's fire season will be less severe. In forests, the opposite is often true; although dry spells diminish kindling, they also make vegetation more combustible. The findings, in the May *Bulletin of the American Meteorological Society*, could help douse blazing costs: U.S. agencies spent more than $1 billion fighting the fires that ravaged some 6.4 million acres last year. *—Sarah Simpson*

PHYSICS

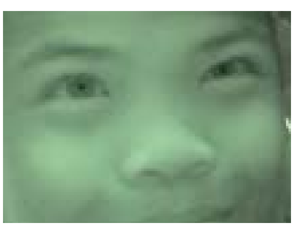
Forced Attraction

Opposites attract and like repels, at least when it comes to electricity and magnetism. Now physicists suggest that it could be possible to bind positive charges to other positive charges. The result could be otherwise impossible "molecules," in which proton-loaded atomic nuclei stick together without electrons. The trick: high-power lasers, which could push atomic nuclei and keep them spinning around one another instead of exploding apart. Sufficiently intense laser pulses could then slam the nuclei together. Such experiments could boost understanding about nuclear activity in stars and improve laser-driven fusion reactor design. The hope is that tabletop equipment could generate fast enough laser pulses for nuclei confinement or collision. The team at the National Research Council Canada in Ottawa presents its findings in the June 20 *Physical Review Letters*. *—Charles Choi*

BIOLOGY

See under the Sea

Clear vision certainly helps get the job done. For the Moken people, who live along the coasts of Myanmar and Thailand, that means being able to spot clams, sea cucumbers and other food on the ocean bottom. But as any swimmer knows, blurriness rules underwater. Anna Gislén of Lund University in Sweden and her colleagues have uncovered an unusual adaptation: unlike European kids, Moken children "accommodate," or focus on objects, when they are underwater. Moreover, the Moken reduce the size of their pupils, a reflex resulting from accommodation and perhaps from a physiological response to diving. Like a pinhole camera, an eye with a smaller pupil produces sharper images. The adaptations enable the Moken to see twice as well underwater as landlubbers do. Gislén is testing Swedish children to determine if underwater focusing can be learned. "Preliminary data suggest this ability is very much trainable," she remarks. The May 13 *Current Biology* contains the report. *—Philip Yam*



CONSTRICTED PUPILS show that the Moken can focus underwater.

DAVID McNEW *Getty (top)*; PIERRE PERRIN *Corbis Sygma (bottom)*

BRIEF POINTS

- **A common gene therapy vector, a leukemia retrovirus, integrates its genes near active genes, possibly disrupting them. Researchers previously thought that the integration occurred randomly and thus did not pose a hazard to a patient's genes. The finding may explain recent failed trials in which patients developed leukemia.**

  Science, June 13, 2003

- **Keep the mystique: Rather than wearing casual clothing such as jeans and sneakers, physicians are better off donning white lab coats with name tags. Patients feel that such attire projects confidence and inspires trust.**

  Archives of Internal Medicine, June 9, 2003

- **A noise thermometer can go from near absolute zero to room temperature. Made of metal strips around an insulator, it depends on the tunneling of electrons, which creates temperature-dependent "shot" noise.**

  Science, June 20, 2003

- **Saturn's winds have died down from 1,700 kilometers per hour in the early 1980s to a current speed of 1,000 kph—a result perhaps of the planet's long seasonal cycles and equatorial shadows cast by its rings.**

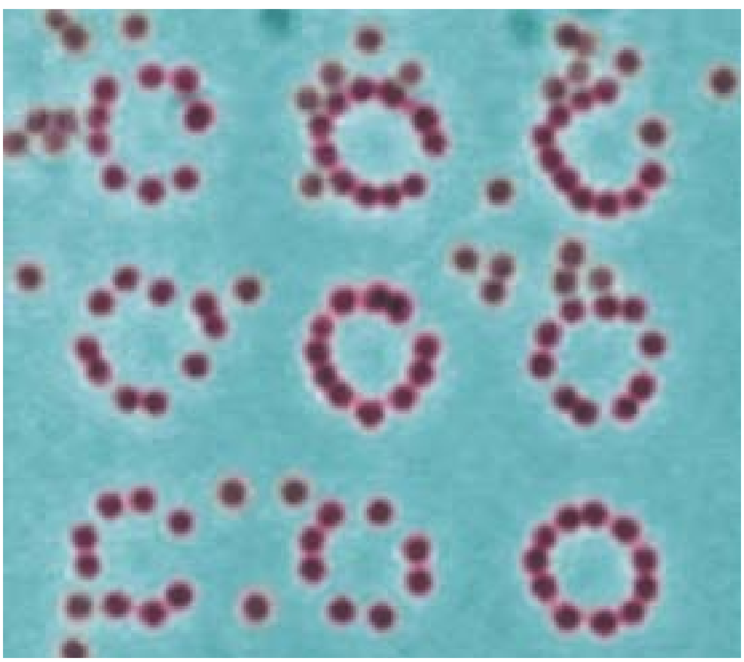
  Nature, June 5, 2003

Hands of Light

Moving particles with photons leads to a new form of nanomanufacturing By GARY STIX

When David G. Grier got a tenure-track teaching position at the University of Chicago in 1992, he expected to continue the work on high-temperature superconductors that he had completed as a postdoctoral fellow at Bell Labs. Biding his time while his superconductor laboratory was being set up, he decided to carry out what he thought would be a quick and easy experiment on suspensions of particles, called colloids. These materials serve as a means for scientists to study how the atoms in metal crystals or other collections of tiny particles interact with one another, without having to move around individual atoms.

"We whipped up the experiment, and nothing was what it was supposed to be," Grier says. One-micron-diameter latex beads carrying a negative electrical charge had demonstrated a strong attraction when they were placed in a solution of water between two closely spaced parallel plates also bearing a negative charge. "It contradicted a 50-year-old theory that holds that like charges in a solution repel," he adds. The technology needed to understand the colloids was one that he had learned to use at Bell Labs, where it had been invented.



OPTICAL VORTICES generated by a laser beam drive microscopic beads in circles.

Optical tweezers employ forces applied by a highly focused laser beam to trap and move objects ranging in size from that of a protein (five nanometers) up to that of a collection of dozens of cells (100 microns). The tweezers trap the particles where the light is most intense. Grier and his students manipulated two tweezers to measure the interaction between microscopic beads. Each tweezer captured one bead and, when the trap was turned off, released it. The group then observed with a digital-video microscope how quickly the two beads moved toward or away from each other, enabling a calculation of the forces exerted by one bead on another. But the researchers needed to do more. They wanted to see whether this attractive force exists among complex configurations of particles. This finding might afford a better comprehension of biological systems—how DNA and proteins, for instance, pack tightly together in the cell nucleus. But aligning multiple optical tweezers to measure forces among even four particles was difficult.

One student, Eric R. Dufresne, was looking through a surplus catalogue and came across a $5 device that separates the beam from a laser pointer into a four-by-four array that fans out from the original beam. "It was worth trying for five bucks, but we thought we shouldn't be disappointed if it didn't pan out," Grier recalls. The experiment proceeded without a hitch. "We wrote it up and patented it," he says.

The patent covers the use of a computer-designed diffraction grating, a type of hologram that takes a single beam and breaks it up into an array of beams, each one of which forms an optical trap for particles of micron or nanometer dimensions. The invention transcends the run-of-the-mill optical tweezers. Regular

JENNIFER E. CURTIS, BRIAN A. KOSS AND DAVID G. GRIER *University of Chicago* light pincers are often compared to chopsticks or paired fingers. Holographic optical tweezers, as they are called, are more akin to a hand, with its ability to move fingers independently at various angles.

The $5 solution paved the way to the next, more challenging problem. The diffraction gratings purchased from the catalogue were limited to 16 beams and did not allow the beams to be manipulated independently. But Grier and his team already foresaw the possibility of maneuvering hundreds or even thousands of particles in a three-dimensional space. They tried a variety of approaches—ranging from chip-making lithography tools to liquid-crystal displays such as those used in a Sony Watchman—that would allow them to create and control diffracted beams separately. "This was a slow and difficult process to get something working," Grier remembers.

The answer came in the form of liquid-crystal spatial light modulators used in pattern matching for fingerprint identification and retinal scanning. By changing the orientation of the molecules that make up the liquid crystals, the modulators reshape the wavefront of the incoming light beam to display the image encoded in a computer-designed hologram. The pattern on the hologram can project hundreds or thousands of beams that can be moved forward, back, sideways, up or down or can twist the light in a corkscrew trajectory that creates a vortex.

The tweezer array showed successfully that the same attraction that occurs between a pair of similarly charged particles is also present in large clusters of them. And the researchers realized that the technology might be good for other things. "People were asking, 'What are the applications?'" Grier says. "At that point we didn't have any. We had a lot of ideas, but very few of them had been demonstrated." The university technology office shopped the idea around. Lewis Gruber, a co-founder of a biotechnology company called Hyseq (now Nuvelo), had retired to Chicago and was contacted by the university. When Grier and his students demonstrated the tweezer array, Gruber was impressed: "It's bigger than genomics. It was the most exciting thing I had ever seen." Gruber perceived that the tweezer array was not just a tool for biology but could be used in manufacturing materials for markets from photonics to food processing.

In late fall of 2000, a few months after witnessing Grier's demonstration, Gruber had licensed the patents held by the University of Chicago to start a new company. The first few employees, along with the members of Grier's lab, were asked to come up with a name. Grier's suggestion of the Very Nice Optical Tweezer Company was immediately vetoed. Then he remembered that high-tech companies were supposed to have names studded with letters like "X" or "Q." Thus was born Arryx. The company set up quarters on two basement floors in downtown Chicago, just down the street from the signature Wrigley building.

Arryx developed a point-and-click system that allows a particle to be imaged, highlighted, trapped and moved along a trajectory outlined on the screen. With the telecommunications boom at its peak, the company began to research using holographic optical tweezers to make photonic crystals that could switch or amplify optical signals. Tweezer arrays with dozens of beams could manipulate particles to create defects in an ordered colloidal crystal. Thus altered, the crystals could form components for optical networks, such as a device that channels light signals around corners with very low loss in energy.

Optical tweezer arrays are not just for biology but could be used in markets from photonics to food processing.

After the telecom market imploded, the technology demonstrated the versatility that Gruber had originally perceived. The evaporation in demand for next-generation optical networks caused Arryx to turn its sights toward biology. Its first product, the BioRyx 200, is a $275,000 research tool sold to the likes of Emory University and the National Institute of Standards and Technology. The company's first application-specific products will try to best the efficiency of conventional flow cytometry techniques, sorting hundreds or thousands of cells at once. Further elaboration of the technology may enable sorting of cells or proteins more quickly and precisely than an approach known as gel electrophoresis. The work on photonic crystals was not for naught, though. These devices may soon be incorporated into the manufacture of optical sensors for detection of bioweapons or toxic chemicals.

Optical tweezers are more than a hand of light. They are more like a hand that has power screwdrivers or cutting tools attached to the tips of each finger. Each beam can apply torque to an object or make incisions in a material. In the future, holographic tweezers may assemble nanocomputers from carbon nanotubes, purify drugs, perform noninvasive surgery or create spinning liquid vortices that act as microscopic pumps. This diversity may allow holographic optical tweezers to become a critical tool in the still emerging disciplines of nanotechnology and microelectromechanics. SA

What a Little Limeade Can Do

Owning the rights for frozen juice to treat angina and for lunar birth control By GARY STIX

A patent gives the holder the right to exclude others from making, using or selling an invention for 20 years from the filing date. The holders of the following selection of patents—a continuation of last month's column on out-of-the-ordinary issuances from the U.S. Patent and Trademark Office—will probably not have to worry too much about having to mount an aggressive program to protect their intellectual property.

Method of treating chest pain, patent 6,457,474, Carl E. Hanson of St. Paul, Minn. This inventor has patented lime juice to replace nitroglycerin as a treatment for chest pain such as angina pectoris. Making the patented invention requires only modest skill. "Limeade in non-concentrated form," according to the document, "was prepared by opening a can of the Minute Maid brand Premium All Natural Frozen Concentrate for Limeade, removing the contents and placing it in a pitcher, adding approximately 52 fluid ounces (about 4.5 cans) of tap water to the frozen concentrate and stirring.

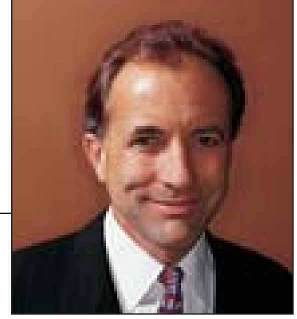
"The pitcher was placed in the refrigerator so that the contents would cool. I drank approximately 2 to 3 glasses of limeade daily and did not notice the reoccurrence of chest pain." The lime juice can also be administered intravenously or by the angina sufferer's placing the frozen concentrate directly into his or her mouth. "The present invention is advantageous in that a patient can easily determine if the medicine is properly ingested. Lime juice has a very noticeable taste that disappears after it leaves the mouth. Since the juice is regularly stored in the refrigerator or freezer, it can be quickly located by the patient, particularly at nighttime where the refrigerator light plays a helpful role."

Process for phase-locking human ovulation/menstrual cycles, patent 6,497,718, assigned to the secretary of the U.S. Air Force. "By simulating moonlight with nocturnal light exposures [with a 100-watt lightbulb], the menstrual cycles of women could be brought nearer to the lunar cycle of 29.5 days.... The idea behind it is that, during evolution, the fertility cycle of humans and other primates was phase-locked to the moon and that [the] full moon coincided with ovulation.... It would also explain, on a rational basis, the cause of the well-known 'romantic' effect of the full moon." The technique, notes the patent, would allow the rhythm method to be more reliably adopted.

Talking moving dieter's plate, patent 6,541,713, Albertine White of Los Angeles. "This invention provides a plate and scale combination with a pre-programmed repertoire of statements which can be made by the device depending on the stimulus. The apparatus can be programmed to encourage dieters not to place excessive meal portions on the plate or, alternatively, it can be programmed to encourage persons battling anorexia to have normal sized meals rather than meals which are too small.... The invention might roll away from the dieter, or a lid might close, denying access to the food. The invention might tremble in 'anxiety' over the amount of food being measured or the invention might even be able to flush the food into itself if too great a portion is measured."

Apparatus and method for detecting and identifying organisms, especially pathogens, using the aura signature of the organism, patent 6,466,688, Thomas P. Ramstack of Silver Spring, Md. A technology for detecting "auras," or "electromagnetic fields created by the action of the cells of all living organisms." It purportedly screens for pathogens involved in disease or biowarfare. "Typically, the auras of diseased persons bear telltale colors, and the auras may have holes or gaps not normally present in healthy persons. An illness can often be detected as a dark brown glow in a person's aura." SA

JENNIFER KANE



The Ignoble Savage

Science reveals humanity's heart of darkness By MICHAEL SHERMER

In 1670 English poet John Dryden penned this expression of humans in a state of nature: "I am as free as Nature first made man . . . / When wild in woods the noble savage ran." A century later, in 1755, French philosopher Jean-Jacques Rousseau canonized the noble savage in Western culture by proclaiming that "nothing can be more gentle than he in his primitive state, when placed by nature at an equal distance from the stupidity of brutes and the pernicious good sense of civilized man."

From the Disneyfication of Pocahontas to Kevin Costner's eco-pacifist Native Americans in *Dances with Wolves* and from postmodern accusations of corruptive modernity to modern anthropological theories that indigenous people's wars are just ritualized games, the noble savage remains one of the last epic creation myths of our time.

"Anthropologists have searched for peaceful societies much like Diogenes looked for an honest man."

Science reveals a rather different picture of humanity in its natural state. In a 1996 study University of Michigan ecologist Bobbi S. Low analyzed 186 preindustrial societies and discovered that their relatively low environmental impact is the result of low population density, inefficient technology and lack of profitable markets, not conscious efforts at conservation. Anthropologist Shepard Krech III, in his 1999 book *The Ecological Indian,* shows that in a number of Native American communities, large-scale irrigation practices led to the collapse of their societies.

Even the reverence for big game animals that we have been told was held by Native Americans is a fallacy—many believed that common game animals such as elk, deer, caribou, beaver and especially buffalo would be physically reincarnated, thus easily replaced, by the gods. Given the opportunity to hunt big game animals to extinction, they did. The evidence is now overwhelming that many large mammals went extinct at the same time that the first Americans began to populate the continent.

Ignoble savages were nasty to one another as well as to their environments. Surveying primitive and civilized societies, University of Illinois anthropologist Lawrence H. Keeley, in his 1996 book *War before Civilization,* demonstrates that prehistoric war was, relative to population densities and fighting technologies, at least as frequent (measured in years at war versus years at peace), as deadly (determined by percentage of deaths resulting from conflict) and as ruthless (judged by the killing and maiming of noncombatants, women and children) as modern war. One pre-Columbian mass grave in South Dakota, for example, yielded the remains of 500 scalped and mutilated men, women and children.

In *Constant Battles,* a recent and exceptionally insightful study of this concept, Harvard University archaeologist Steven A. LeBlanc quips, "Anthropologists have searched for peaceful societies much like Diogenes looked for an honest man." Consider the evidence from a 10,000-year-old Paleolithic site along the Nile River: "The graveyard held the remains of 59 people, at least 24 of whom showed direct evidence of violent death, including stone points from arrows or spears within the body cavity, and many contained several points. There were six multiple burials, and almost all those individuals had points in them, indicating that the people in each mass grave were killed in a single event and then buried together."

LeBlanc's survey reveals that even cannibalism, long thought to be a form of primitive urban legend (noble savages would never eat one another, would they?), is supported by powerful physical artifacts: broken and burned bones, cut marks on bones, bones cracked open lengthwise to get at the marrow, and bones inside cooking jars hacked so that they would fit. Such evidence for prehistoric cannibalism has been uncovered in Mexico, Fiji and parts of Europe. The definitive (and gruesome) proof came with the discovery of the human muscle protein myoglobin in the fossilized human feces of a prehistoric Anasazi pueblo Indian. Savage, yes. Noble, no.

Roman statesman Cicero noted, "Although physicians frequently know their patients will die of a given disease, they never tell them so. To warn of an evil is justified only if, along with the warning, there is a way of escape." As we shall see in part two of this column, there is an escape from our disease. SA

Michael Shermer is publisher of Skeptic *(www.skeptic.com) and author of* Why People Believe Weird Things.

BRAD HINES

CENSORS of the

Biologists have been surprised to discover that most animal and plant cells contain a built-in system to silence individual genes by shredding the RNA they produce. Biotech companies are already working to exploit it

Genome

By Nelson C. Lau and David P. Bartel

Observed on a microscope slide, a living cell appears serene. But underneath its tranquil facade, it buzzes with biochemical chatter. The DNA genome inside every cell of a plant or animal contains many thousands of genes. Left to its own devices, the transcription machinery of the cell would express every gene in the genome at once: unwinding the DNA double helix, transcribing each gene into single-stranded messenger RNA and, finally, translating the RNA messages into their protein forms.

No cell could function amid the resulting cacophony. So cells muzzle most genes, allowing an appropriate subset to be heard. In most cases, a gene's DNA code is transcribed into messenger RNA only if a particular protein assemblage has docked onto a special regulatory region in the gene.

Some genes, however, are so subversive that they should never be given freedom of expression. If the genes from mobile genetic elements were to successfully broadcast their RNA messages, they could jump from spot to spot on the DNA, causing cancer or other diseases. Similarly, viruses, if allowed to express their messages unchecked, will hijack the cell's protein production facilities to crank out viral proteins.

Cells have ways of fighting back. For example, biologists long ago identified a system, the interferon response, that human cells deploy when viral genes enter a cell. This response can shut off almost all gene expression, analogous to stopping the presses. And just within the past several years, scientists have discovered a more precise and—for the purposes of research and medicine—more powerful security apparatus built into nearly all plant and animal cells. Called RNA interference, or RNAi, this system acts like a censor. When a threatening gene is expressed, the RNAi machinery silences it by intercepting and destroying only the offender's messenger RNA, without disturbing the messages of other genes.

As biologists probe the modus operandi of this cellular censor and the stimuli that spur it into action, their fascination and excitement are growing. In principle, scientists might be able to invent ways to direct RNA interference to stifle genes involved in cancer, viral infection or other diseases. If so, the technology could form the basis for a new class of medicines.

Meanwhile researchers working with plants, worms, flies and other experimental organisms have already learned how to co-opt RNAi to suppress nearly any gene they want to study, allowing them to begin to deduce the gene's purpose. As a research tool, RNAi has been an immediate success, allowing hundreds of laboratories to tackle questions that were far beyond their reach just a few years ago.

JANA BRENNING

PURPLE PETUNIAS offered the first clues to the existence of gene censors in plants. When extra pigment genes were inserted into normal plants (*left*), the flowers that emerged ended up with areas that strangely lacked color (*center* and *right*).

RICHARD A. JORGENSEN *University of Arizona*

Whereas most research groups are using RNA interference as a means to an end, some are investigating exactly how the phenomenon works. Other labs (including our own) are uncovering roles for the RNAi machinery in the normal growth and development of plants, fungi and animals—humans among them.

A Strange Silence

THE FIRST HINTS of the RNAi phenomenon surfaced 13 years ago. Richard A. Jorgensen, now at the University of Arizona, and, independently, Joseph Mol of the Free University of Amsterdam inserted into purple-flowered petunias additional copies of their native pigment gene. They were expecting the engineered plants to grow flowers that were even more vibrantly violet. But instead they obtained blooms having patches of white.

Jorgensen and Mol concluded that the extra copies were somehow triggering censorship of the purple pigment genes—including those natural to the petunias—resulting in variegated or even albino-like flowers. This dual censorship of an inserted gene and its native counterpart, called co-suppression, was later seen in fungi, fruit flies and other organisms.

Clues to the mystery of how genes were being silenced came a few years later from William G. Dougherty's lab at Oregon State University. Dougherty and his colleagues started with tobacco plants that had been engineered to contain within their DNA several copies of the CP (coat protein) gene from tobacco etch virus. When these plants were exposed to the virus, some of the plants proved immune to infection. Dougherty proposed that this immunity arose through co-suppression. The plants apparently reacted to the initial expression of their foreign CP genes by shutting down this expression and subsequently also blocking expression of the CP gene of the invading virus (which needed the coat protein to produce an infection). Dougherty's lab went on to show that the immunity did not require synthesis of the coat protein by the plants; something about the RNA transcribed from the CP gene accounted for the plants' resistance to infection.

The group also showed that not only could plants shut off specific genes in viruses, viruses could trigger the silencing of selected genes. Some of Dougherty's plants did not suppress their CP genes on their own and became infected by the virus, which replicated happily in the plant cells. When the researchers later measured the RNA being produced from the CP genes of the affected plants, they saw that these messages had nearly vanished—infection had led to the CP genes' inactivation.

Meanwhile biologists experimenting with the nematode *Caenorhabditis elegans,* a tiny, transparent worm, were puzzling over their attempts to use "antisense" RNA to inactivate the genes they were studying. Antisense RNA is designed to pair up with a particular messenger RNA sequence in the same way that two complementary strands of DNA mesh to form a double helix. Each strand in DNA or RNA is a chain of nucleotides, genetic building blocks represented by the letters A, C, G and either U (in RNA) or T (in DNA). C nucleotides link up with Gs, and As pair with Us or Ts. A strand of antisense RNA binds to a complementary messenger RNA strand to form a double-stranded structure that cannot be translated into a useful protein.

Over the years, antisense experiments in various organisms have had only spotty success. In worms, injecting antisense RNAs seemed to work. To everyone's bewilderment, however, "sense" RNA also blocked gene expression. Sense RNA has the same sequence as the target messenger RNA and is therefore unable to lock up the messenger RNA within a double helix.

The stage was now set for the eureka experiment, performed five years ago in the labs of Andrew Z. Fire of the Carnegie Institution of Washington and Craig C. Mello of the University of Massachusetts Medical School. Fire and Mello guessed that the previous preparations of antisense and sense RNAs that were being injected into worms were not totally pure. Both mixtures probably contained trace amounts of double-stranded RNA. They

Overview/*RNA Interference*

- Scientists have long had the ability to introduce altered genes into experimental organisms. But only within the past few years have they discovered a convenient and effective way to turn off a specific gene inside a cell.
- It turns out that nearly all plant and animal cells have internal machinery that uses unusual forms of RNA, the genetic messenger molecule, to naturally silence particular genes.
- This machinery has evolved both to protect cells from hostile genes and to regulate the activity of normal genes during growth and development. Medicines might also be developed to exploit the RNA interference machinery to prevent or treat diseases.

suspected that the double-stranded RNA was alerting the censors.

To test their idea, Fire, Mello and their colleagues inoculated nematodes with either single- or double-stranded RNAs that corresponded to the gene *unc-22,* which is important for muscle function. Relatively large amounts of single-stranded *unc-22* RNA, whether sense or antisense, had little effect on the nematodes. But surprisingly few molecules of double-stranded *unc-22* RNA caused the worms—and even the worms' offspring—to twitch uncontrollably, an unmistakable sign that something had started interfering with *unc-22* gene expression. Fire and Mello observed the same amazingly potent silencing effect on nearly every gene they targeted, from muscle genes to fertility and viability genes. They dubbed the phenomenon "RNA interference" to convey the key role of double-stranded RNA in initiating censorship of the corresponding gene.

Investigators studying plants and fungi were also closing in on double-stranded RNA as the trigger for silencing. They showed that RNA strands that could fold back on themselves to form long stretches of double-stranded RNA were potent inducers of silencing. And other analyses revealed that a gene that enables cells to convert single-stranded RNA into double-stranded RNA was needed for co-suppression. These findings suggested that Jorgensen and Mol's petunias recognized the extra pigment genes as unusual (through a mechanism that is still mysterious) and converted their messenger RNAs into double-stranded RNA, which then triggered the silencing of both the extra and native genes. The concept of a double-stranded RNA trigger also explains why viral infection muzzled the CP genes in Dougherty's plants. The tobacco etch virus had created double-stranded RNA of its entire viral genome as it reproduced, as happens with many viruses. The plant cells responded by cutting off the RNA messages of all genes associated with the virus, including the CP genes incorporated into the plant DNA.

Biologists were stunned that such a powerful and ubiquitous system for regulating gene expression had escaped their notice for so long. Now that the shroud had been lifted on the phenomenon, scientists were anxious to analyze its mechanism of action and put it to gainful employment.

Slicing and Dicing Genetic Messages

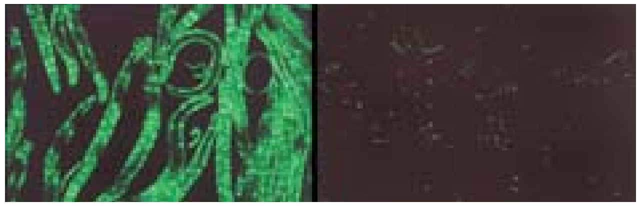
RNA INTERFERENCE was soon observed in algae, flatworms and fruit flies—diverse branches of the evolutionary tree. Demonstrating RNAi within typical cells of humans and other mammals was considerably trickier, however.

When a human cell is infected by viruses that make long double-stranded RNAs, it can slam into lockdown mode: an enzyme known as PKR blocks translation of all messenger RNAs—both normal and viral—and the enzyme RNAse L indiscriminately destroys the messenger RNAs. These responses to double-stranded RNA are considered components of the so-called interferon response because they are triggered more readily after the cells have been exposed to interferons, molecules that infected cells secrete to signal danger to neighboring cells.

Unfortunately, when researchers put artificial double-stranded RNAs (like those used to induce RNA interference in worms and flies) into the cells of mature mammals, the interferon response indiscriminately shuts down every gene in the cell. A deeper understanding of how RNA interference works was needed before it could be used routinely without setting off the interferon alarms. In addition to the pioneering researchers already mentioned, Thomas Tuschl of the Rockefeller University, Phillip D. Zamore of the University of Massachusetts Medical School, Gregory Hannon of Cold Spring Harbor Laboratory in New York State and many others have added to our current understanding of the RNA interference mechanism.

RNAi appears to work like this: Inside a cell, double-stranded RNA encounters an enzyme dubbed Dicer. Using the chemical process of hydrolysis, Dicer cleaves the long RNA into pieces, known as short (or small) interfering RNAs, or siRNAs. Each siRNA is about 22 nucleotides long.

Dicer cuts through both strands of the long double-stranded RNA at slightly staggered positions so that each resulting siRNA has two overhanging nucleotides on one strand at either



GLOWING NEMATODES proved that RNA interference operates in animals as well as plants. When worms whose cells express a gene for a fluorescent protein (*left*) were treated with double-stranded RNA corresponding to the gene, the glow was extinguished (*right*).

Surprisingly FEW MOLECULES of double-stranded RNA made the worms—and even their offspring—TWITCH UNCONTROLLABLY.

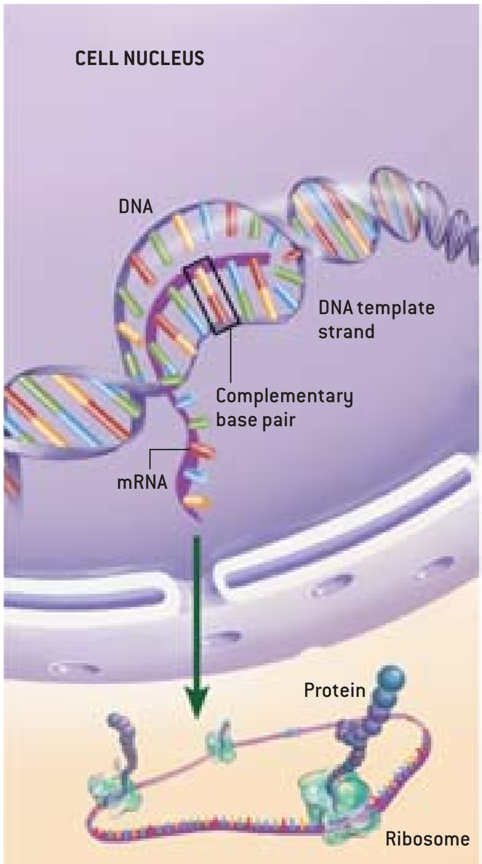
COURTESY OF LISA TIMMONS *University of Kansas;* TIMMONS ET AL. IN *GENE,* VOL. 263; 2001

THE AUTHORS

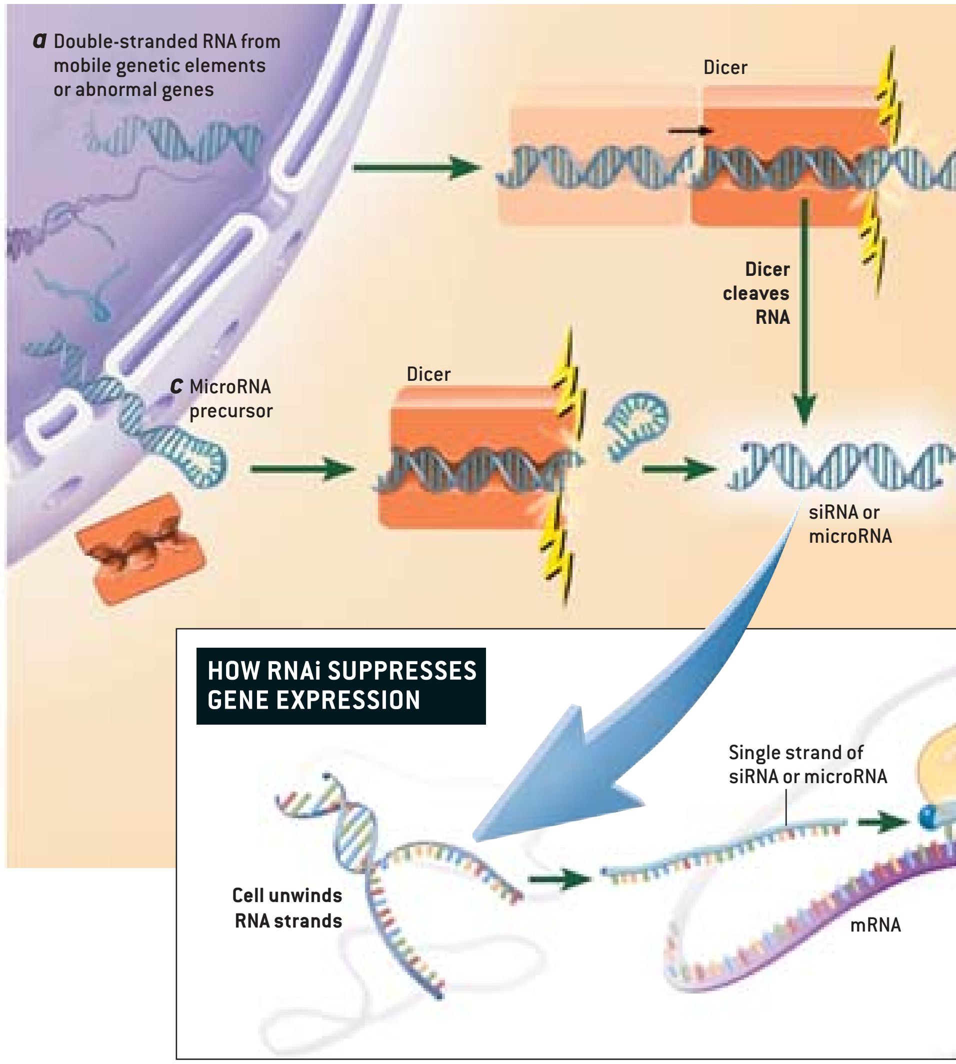
NELSON C. LAU and *DAVID P. BARTEL* have been studying microRNAs and other small RNAs that regulate the expression of genes. Lau is completing a doctoral degree at the Whitehead Institute and the Massachusetts Institute of Technology. Bartel started his research group at the Whitehead Institute in 1994, after earning a Ph.D. at Harvard University. Bartel is also an associate professor at M.I.T. and a co-founder of Alnylam Pharmaceuticals, which is developing RNAi-based therapeutics. Lau and Bartel are among the recipients of the 2002 AAAS Newcomb Cleveland Prize.

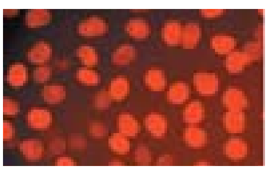
GENETIC CENSORSHIP: HOW IT WORKS

NORMAL GENE EXPRESSION



TRIGGERS OF RNA SILENCING





GLOWING CELLS reveal successful translation of a gene (encoding the lamin protein) into protein form.

end [*see box above*]. The siRNA duplex is then unwound, and one strand of the duplex is loaded into an assembly of proteins to form the RNA-induced silencing complex (RISC).

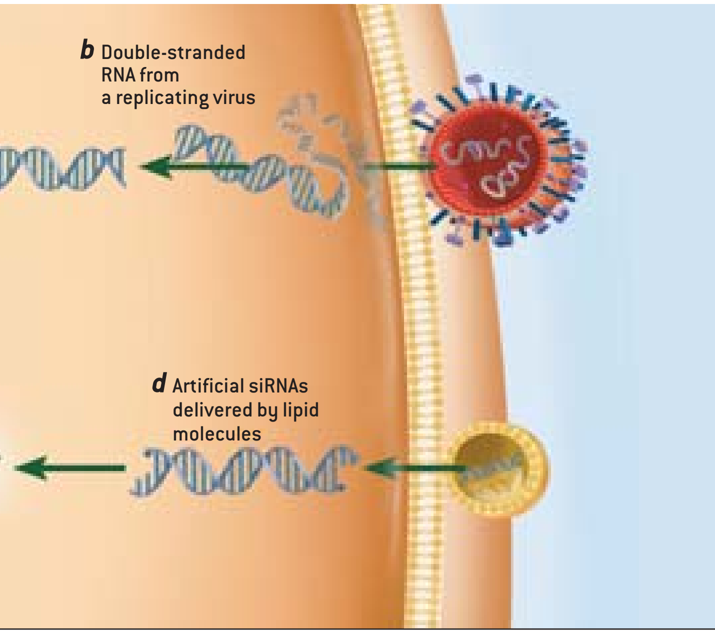
Within the silencing complex, the siRNA molecule is positioned so that messenger RNAs can bump into it. The RISC will encounter thousands of different messenger RNAs that are in a typical cell at any given moment. But the siRNA of the RISC will adhere well only to a messenger RNA that closely complements its own nucleotide sequence. So, unlike the interferon response, the silencing complex is highly selective in choosing its target messenger RNAs.

When a matched messenger RNA finally docks onto the siRNA, an enzyme known as Slicer cuts the captured messenger RNA strand in two. The RISC then releases the two messenger RNA pieces (now rendered incapable of directing protein synthesis) and moves on. The RISC itself stays intact, free to find and cleave another messenger RNA. In this way, the RNAi censor uses bits of the double-stranded RNA as a blacklist to identify and mute corresponding messenger RNAs.

David C. Baulcombe and his co-workers at the Sainsbury Laboratory in Norwich, England, were the first to spot siRNAs, in plants. Tuschl's group later isolated them from fruit fly embryos and demonstrated their role in gene silencing by synthesizing artificial siRNAs and using them to direct the destruction of messenger RNA targets. When that succeeded, Tuschl wondered whether these short snippets of RNA might slip under the radar of mammalian cells without setting off the interferon response, which generally ignores double-stranded RNAs that are shorter than 30 nucleotide pairs. He and his co-workers put synthetic siRNAs into cultured mammalian cells, and the experiment went just as they expected. The target genes were silenced; the interferon response never occurred.

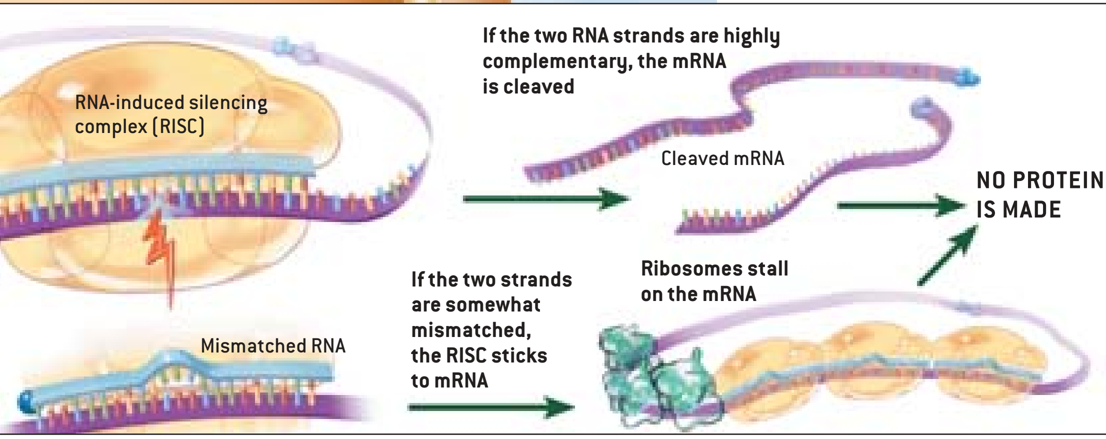
Tuschl's findings rocked the biomedical community. Geneticists had long been able to introduce a new gene into mammalian cells by, for example, using viruses to ferry the gene into cells. But it would take labs months of labor to knock out a gene

TERESE WINSLOW; THOMAS TUSCHL *The Rockefeller University (micrographs)*



A CELL CAN CENSOR the expression of an individual gene inside it by interfering with the messenger RNA (mRNA) transcribed from the offending gene, thus preventing the RNA from being decoded by ribosomes into active protein, as normally happens (*left panel*). The censorship machinery is triggered by small, double-stranded RNA molecules with ragged ends. An enzyme called Dicer chemically snips such short interfering RNAs (siRNAs) from longer double-stranded RNAs produced by self-copying genetic sequences (*a*) or viruses (*b*). Regulatory RNA sequences known as microRNA precursors (*c*) are also cleaved by Dicer into this short form. And scientists can use lipid molecules to insert artificial siRNAs into cells (*d*).

The RNA fragments separate into individual strands (*bottom panel*), which combine with proteins to form an RNA-induced silencing complex (RISC). The RISC then captures mRNA that complements the short RNA sequence. If the match is essentially perfect, the captive message is sliced into useless fragments (*top row*); less perfect matches elicit a different response. For instance, they may cause the RISC to block ribosome movements and thus halt translation of the message into protein form (*bottom row*).



GLOW FADED in cells that took up artificial siRNAs corresponding to the lamin gene.

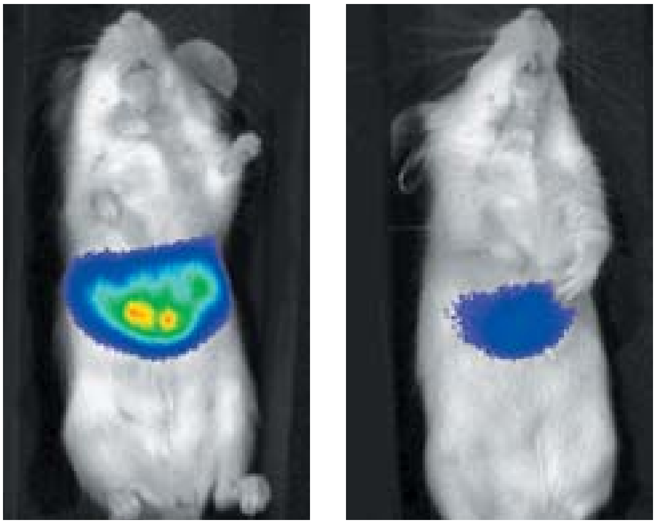
of interest to ascertain the gene's function. Now the dream of easily silencing a single, selected gene in mammalian cells was suddenly attainable. With siRNAs, almost any gene of interest can be turned off in mammalian cell cultures—including human cell lines—within a matter of hours. And the effect persists for days, long enough to complete an experiment.

A Dream Tool

AS HELPFUL AS RNA interference has become to mammal biologists, it is even more useful at the moment to those who study lower organisms. A particular bonus for those studying worms and plants is that in these organisms the censorship effect is amplified and spread far from the site where the double-stranded RNA was introduced. This systemic phenomenon has allowed biologists to exploit RNAi in worms simply by feeding them bacteria engineered to make double-stranded RNA corresponding to the gene that should be shut down.

Because RNA interference is so easy to induce and yet so powerful, scientists are thinking big. Now that complete genomes—all the genes in the DNA—have been sequenced for a variety of organisms, scientists can use RNA interference to explore systematically what each gene does by turning it off. Recently four groups did just that in thousands of parallel experiments, each disabling a different gene of *C. elegans*. A similar genome-wide study is under way in plants, and several consortia are planning large RNAi studies of mammalian cells.

RNA interference is being used by pharmaceutical companies as well. Some drug designers are exploiting the effect as a shortcut to screen all genes of a certain kind in search of promising targets for new medicines. For instance, the systematic silencing of genes using RNAi could allow scientists to find a gene that is critical for the growth of certain cancer cells but not so important for the growth of normal cells. They could then develop a drug candidate that interferes with the protein product of this gene and then test the compound against cancer. Biotech firms have also been founded on the bet that gene silencing by



MICE LIGHT UP when injected with DNA containing the luciferase gene (*left*). But scientists took the shine off the mice by also injecting siRNAs that match the gene (*right*), thus demonstrating one way to exploit RNAi in mammals.

RNAi could itself become a viable therapy to treat cancer, viral infections, certain dominant genetic disorders and other diseases that could be controlled by preventing selected genes from giving rise to illness-causing proteins.

Numerous reports have hinted at the promise of siRNAs for therapy. At least six labs have temporarily stopped viruses—HIV, polio and hepatitis C among them—from proliferating in human cell cultures. In each case, the scientists exposed the cells to siRNAs that prompted cells to shut down production of proteins crucial to the pathogens' reproduction. More recently, groups led by Judy Lieberman of Harvard Medical School and Mark A. Kay of the Stanford University School of Medicine have reported that siRNAs injected under extremely high pressure into mice slowed hepatitis and rescued many of the animals from liver disease that otherwise would have killed them.

Despite these laboratory successes, it will be years before RNAi-based therapies can be used in hospitals. The most difficult challenge will probably be delivery. Although the RNAi effect can spread throughout a plant or worm, such spreading does not seem to occur in humans and other mammals. Also, siRNAs are very large compared with typical drugs and cannot be taken as pills, because the digestive tract will destroy them rather then absorb them. Researchers are testing various ways to disseminate siRNAs to many organs and to guide them through cells' outer membranes. But it is not yet clear whether any of the current strategies will work.

Another approach for solving the delivery problem is gene therapy. A novel gene that produces a particular siRNA might be loaded into a benign virus that will then bring the gene into the cells it infects. Beverly Davidson's group at the University of Iowa, for example, has used a modified adenovirus to deliver genes that produce siRNAs to the brain and liver of mice. Gene therapy in humans faces technical and regulatory difficulties, however.

Regardless of concerns about delivery, RNAi approaches have generated an excitement not currently seen for antisense and catalytic RNA techniques—other methods that, in principle, could treat disease by impeding harmful messenger RNAs. This excitement stems in part from the realization that RNA interference harnesses natural gene-censoring machinery that evolution has perfected over time.

Why Cells Have Censors

INDEED, THE GENE-CENSORING mechanism is thought to have emerged about a billion years ago to protect some common ancestor to plants, animals and fungi against viruses and mobile genetic elements. Supporting this idea, the groups of Ronald H. A. Plasterk at the Netherlands Cancer Institute and of Hervé Vaucheret at the French National Institute of Agricultural Research have shown that modern worms rely on RNA interference for protection against mobile genetic elements and that plants need it as a defense against viruses.

Yet RNA interference seems to play other biological roles as well. Mutant worms and weeds having an impaired Dicer enzyme or too little of it suffer from numerous developmental defects and cannot reproduce. Why should a Dicer deficiency cause animals and plants to look misshapen?

One hypothesis is that once nature developed such an effective mechanism for silencing the subversive genes in viruses and mobile DNA sequences, it started borrowing tools from the RNAi tool chest and using them for different purposes. Each cell has the same set of genes—what makes them different from one another is which genes are expressed and which ones are not. Most plants and animals start as a single embryonic cell that divides and eventually gives rise to a multitude of cells of various types. For this to occur, many of the genes expressed in the embryonic cells need to be turned off as the organ matures. Other genes that are off need to be turned on. When the RNAi machinery is not defending against attack, it apparently pitches in to help silence normal cellular genes during developmental transitions needed to form disparate cell types, such as neurons and muscle cells, or different organs, such as the brain and heart.

What then motivates the RNAi machinery to hush particular normal genes within the cell? In some cases, a cell may nat-

RNAi has temporarily STOPPED VIRUSES—HIV, polio and hepatitis C among them—from proliferating IN HUMAN CELLS.

ANTON P. McCAFFREY ET AL. IN *NATURE*, VOL. 418; JULY 4, 2002; IMAGING SYSTEM COURTESY OF CHRISTOPHER CONTAG

Efforts to Apply RNA Interference to Medicine

THE MACHINERY for RNA interference was discovered to operate in mammals just two years ago. Yet about 10 companies, including the sampling below, have already begun testing ways to exploit gene censoring to treat or prevent human disease. —*The Editors*

COMPANY	PROJECTS	STATUS
Alnylam Pharmaceuticals Cambridge, Mass.	Researching therapeutic applications of RNAi, but specific disease targets not yet announced	Founded in 2002 by Bartel, Tuschl, Sharp and Zamore, the firm has secured initial funding and several patents
Cenix Biosciences Dresden, Germany	Investigating the use of RNAi-based therapies for cancer and viral diseases	With Texas-based Ambion, Cenix is creating a library of siRNAs to cover the entire human genome
Ribopharma Kulmbach, Germany	Attempting to chemically modify siRNAs to make drugs for glioblastoma, pancreatic cancer and hepatitis C	Clinical trials in brain cancer patients are expected to begin this year
Sirna Therapeutics Boulder, Colo.	Testing a catalytic RNA medicine for advanced colon cancer in clinical trials; development of RNAi-based therapeutics is still in early stages	Changed name from Ribozyme Pharmaceuticals in April; recently secured $48 million in venture capital

urally produce long double-stranded RNA specifically for this purpose. But frequently the triggers are "microRNAs"—small RNA fragments that resemble siRNAs but differ in origin. Whereas siRNAs come from the same types of genes or genomic regions that ultimately become silenced, microRNAs come from genes whose sole mission is to produce these tiny regulatory RNAs.

The RNA molecule initially transcribed from a microRNA gene—the microRNA precursor—folds back on itself, forming a structure that resembles an old-fashioned hairpin. With the help of Dicer, the middle section is chopped out of the hairpin, and the resulting piece typically behaves very much like an siRNA—with the important exception that it does not censor a gene with any resemblance to the one that produced it but instead censors some other gene altogether.

As with the RNAi phenomenon in general, it has taken biologists time to appreciate the potential of microRNAs for regulating gene expression. Until recently, scientists knew of only two microRNAs, called *lin-4* RNA and *let-7* RNA, discovered by the groups of Victor Ambros of Dartmouth Medical School and Gary Ruvkun of Harvard Medical School. In the past two years we, Tuschl, Ambros and others have discovered hundreds of additional microRNA genes in worms, flies, plants and humans.

With Christopher Burge at M.I.T., we have estimated that humans have between 200 and 255 microRNA genes—nearly 1 percent of the total number of human genes. The microRNA genes had escaped detection because the computer programs designed to sift through the reams of genomic sequence data had not been trained to find this unusual type of gene, whose final product is an RNA rather than a protein.

Some microRNAs, particularly those in plants, guide the slicing of their mRNA targets, as was shown by James C. Carrington of Oregon State University and Zamore. We and Bonnie Bartel of Rice University have noted that plant microRNAs take aim primarily at genes important for development. By clearing their messages from certain cells during development, RNAi could help the cells mature into the correct type and form the proper structures.

Interestingly, the *lin-4* and *let-7* RNAs, first discovered in worms because of their crucial role in pacing development, can employ a second tactic as well. The messenger RNAs targeted by these microRNAs are only approximately complementary to the microRNAs, and these messages are not cleaved. Some other mechanism blocks translation of the messenger RNAs into productive proteins.

Faced with these different silencing mechanisms, biologists are keeping open minds about the roles of small RNAs and the RNAi machinery. Mounting evidence indicates that siRNAs not only capture messenger RNAs for destruction but can also direct the silencing of DNA—in the most extreme case, by literally editing genes right out of the genome. In most cases, however, the silenced DNA is not destroyed; instead it is more tightly packed so that it cannot be transcribed.

From its humble beginnings in white flowers and deformed worms, our understanding of RNA interference has come a long way. Almost all facets of biology, biomedicine and bioengineering are being touched by RNAi, as the gene-silencing technique spreads to more labs and experimental organisms.

Still, RNAi poses many fascinating questions. What is the span of biological processes that RNA interference, siRNAs and microRNAs influence? How does the RNAi molecular machinery operate at the level of atoms and chemical bonds? Do any diseases result from defects in the RNAi process and in microRNAs? As these questions yield to science, our understanding of the phenomenon will gradually solidify—perhaps into a foundation for an entirely new pillar of genetic medicine. SA

MORE TO EXPLORE

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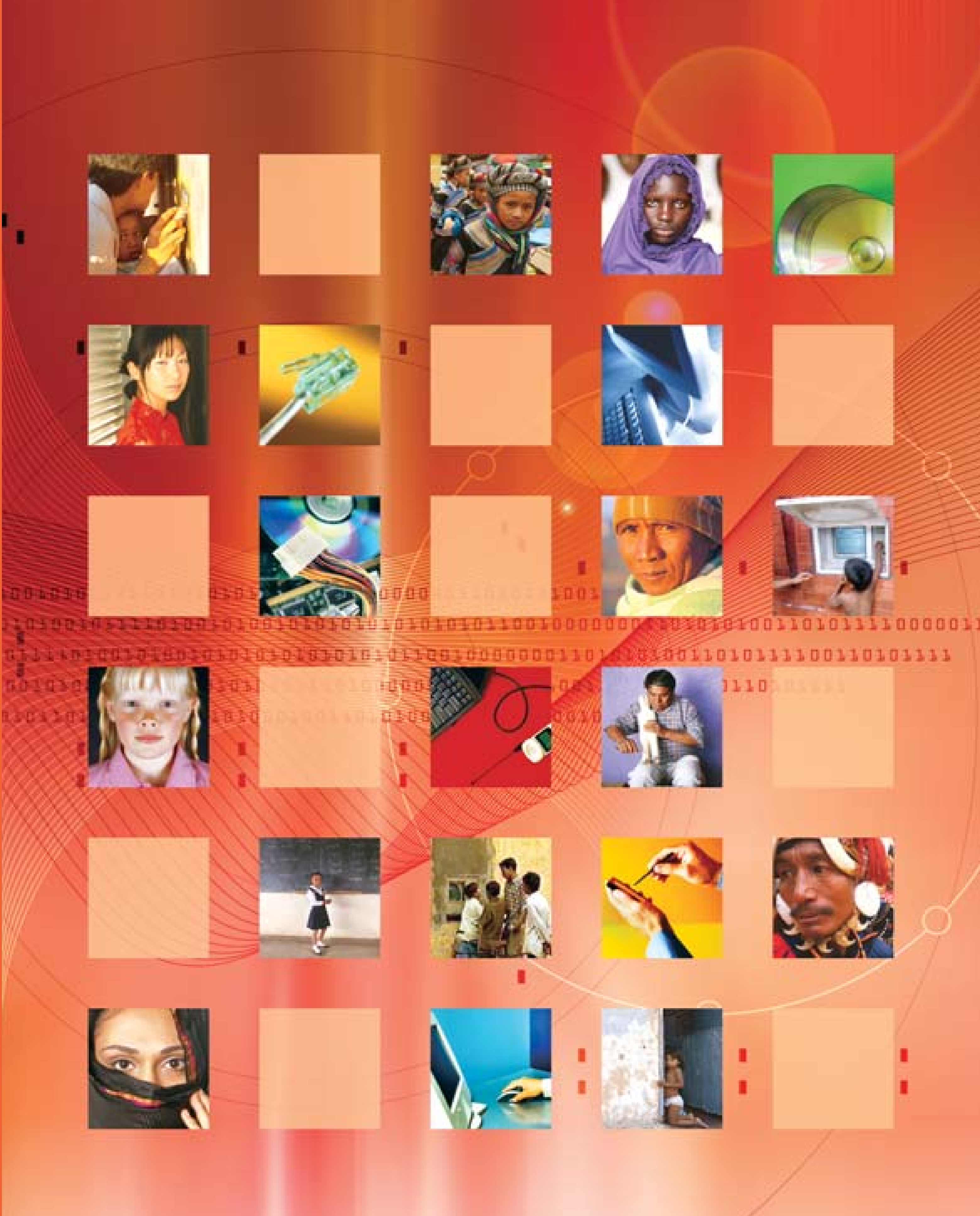
By Mark Warschauer

Demystifying the Digital Divide

The simple binary notion of technology haves and have-nots doesn't quite compute

For much of the past decade, policy leaders and social scientists have grown increasingly concerned about a societal split between those with and those without access to computers and the Internet. The U.S. National Telecommunications and Information Administration popularized a term for this situation in the mid-1990s: the "digital divide." The phrase soon became used in an international context as well, to describe the status of information technology from country to country.

TOM DRAPER DESIGN



LEFT TO RIGHT: NATIONAL INSTITUTE OF INFORMATION TECHNOLOGY, DAVID GREEDY, PHOTODISC, PHOTODISC (*top row*); PHOTODISC (*all photographs in second row*); PHOTODISC, PHOTODISC, MARK WARSCHAUER (*third row*); PHOTODISC, PHOTODISC, KEITH DANNEMILLER *Corbis/SABA* (*fourth row*); KEITH DANNEMILLER *Corbis/SABA*, NATIONAL INSTITUTE OF INFORMATION TECHNOLOGY, PHOTODISC, PHOTODISC (*fifth row*); PHOTODISC, PHOTODISC, VIVIAN MOOS *Corbis* (*bottom row*)

Underlying disparities are real, both within and among countries. The Benton Foundation, which promotes the public-interest use of communications technology, reports that by late 2001, 80 percent of American families with annual household income greater than $75,000 were online, compared with 25 percent of the poorest U.S. families. Total home Internet access was 55 percent for whites, 31 percent for African-Americans and 32 percent for Hispanics. Looking at the international picture, in most African countries less than 1 percent of the population is online. Not surprisingly, such disparity correlates highly with other measures of social and economic inequality.

Yet the simple binary description of a divide fails to do justice to the complex reality of various people's differing access and usage of digital technology. An American who surfs the Internet on a computer at a local library once a month might be considered to be a digital "have-not," whereas someone in a developing country with the same profile would be a "have." Indeed, couching the condition in black-and-white terminology can lead those attempting to deal with technological inequities down the wrong path. The late Rob Kling, who directed the Center for Social Informatics at Indiana University, put it well: "[The] big problem with the 'digital divide' framing is that it tends to connote 'digital solutions,'" that is, "computers and telecommunications," without a consideration of the context into which that hardware would be put.

This line of reasoning led some to assume that the dearth of digital access of nations, communities and individuals could be easily tackled by an infusion of computers and Internet connections. Former Speaker of the U.S. House of Representatives Newt Gingrich has talked about the virtues of giving every child a laptop computer, without offering a solid plan for using the devices. And Bill Gates donated computers to small-town libraries across America, believing that Internet connections would help stem the exodus from rural areas. Although Internet connection through small-town libraries has improved people's lives by allowing them to stay in touch with friends and relatives, it has not stemmed the exodus—which largely depends on broader factors, such as employment availability—and may even have contributed to it by allowing people to search for jobs in cities. (To Gates's and Gingrich's credit, they at least had the issue of technology access on their radar screens. Gates, recognizing the limitations of computer technology in solving social ills, has since gone on to donate billions of dollars to broader health and education campaigns around the world.)

This perspective is known in academic circles as technological determinism, the idea that the mere presence of technology leads to familiar and standard applications of that technology, which in turn bring about social change. The Harvard Graduate School of Education's Christopher Dede has termed this the "fire" model, with its implication that a computer, by its mere presence, will generate learning or development, just as a fire generates warmth. Governments, the private sector, foundations and charities have thus spent hundreds of millions of dollars to bridge the perceived digital divide by providing computers and Internet lines to those in need, often without sufficient attention to the social contexts in which these technologies might be used. (Dede notes that a better model than fire might be clothing, which also keeps one warm yet is tailored for individual fit and use.)

Some assumed that the dearth of digital access could be easily tackled by an infusion of computers.

How does this application based on the assumption of technological determinism turn out in practice? Over the past few years, I have traveled around the world to study community technology programs in both developed and developing countries. I have observed scores of diverse programs and have interviewed hundreds of participants and organizers. As the following case studies show, two basics became apparent: well-intentioned programs often lead in unexpected directions, and the worst failures occur when people attempt to address complex social problems with a narrow focus on provision of equipment.

Overview/*Technologic Logic*

- The concept of a "digital divide" separating those with access to computers and communications technology from those without is simplistic and can lead to well-meaning but incomplete attempts at a solution based on merely adding technology to a given circumstance.
- In fact, people have widely varying opportunities for access to computers and communications technology and disparate reasons for wanting the level of access they may desire.
- A consideration of how people can use computers and the Internet to further the process of social inclusion is paramount in any effort to install new technology into an environment lacking it.

A Minimalist Approach

IN 1999 THE MUNICIPAL government of New Delhi, in collaboration with an Indian company called the National Institute of Information Technology,

PABLO BARTHOLOMEW *Netphotograph.com*

NEW DELHI CHILDREN experiment with what is literally a hole-in-the-wall computer in 2000. The minimally invasive education project was designed to insert technology into the environment so that the children would learn to use the computer without guidance. Without direction, however, the computer proved for the most part to be merely a high-tech toy.

launched an experiment to provide computer access to children in one of the city's poorest areas. Government officials and representatives of the company set up an outdoor kiosk with several computer stations. The computers, with dial-up Internet access, were inside a locked booth, but the monitors, joysticks and buttons stuck out through holes and were accessible. In line with a concept known as minimally invasive education, the test included no teachers or instructors. The idea was to allow the children unfettered daily access so they could learn at their own pace rather than through the directives of adults.

The program was hailed by its organizers as a groundbreaking model for how to bring information technology to the world's urban poor. Inspiring stories circulated on the Internet about how illiterate children taught themselves to use computers and thus crashed the barriers to the information age. These accounts led to additional kiosks being set up in other locations.

My visit to one of the New Delhi kiosks, however, revealed a different picture. The Internet connection seldom functioned. The architecture of the kiosk—based on a wall instead of a room—made instruction or collaboration difficult. Most poor communities in New Delhi already have organizations that work with children and that could have set up educational training at a different kind of computer center, but their participation was neither solicited nor welcomed. Over the nine-month duration of the experiment, the youngsters did indeed learn how to manipulate the joystick and buttons. But without educational programs and with the content primarily in English rather than Hindi, they mostly did what you might expect: played games and used paint programs to draw.

Neighborhood parents felt ambivalent. Several embraced the initiative, but most expressed concern about the lack of organized instruction. Some even complained that the computer was detrimental. "My son used to be doing very well in school," one parent said, "but now he spends all his free time playing computer games at the kiosk, and his schoolwork is suffering." In short, the community came to realize that minimally invasive education was, in practice, minimally effective education.

Nevertheless, an overemphasis on hardware with scant attention paid to the pedagogical and curricular frameworks that shape how the computers are used is common in educational technology projects throughout the world. But such technological determinism has been challenged in the academic arena by a concept called social informatics, which argues that technology must be considered within a specific context that includes hardware, software, support resources, infrastructure, as well as people in various roles and relationships with one another and with other elements of the system. And the technology and social system continuously shape each other, like a biological community and its environment.

Although grassroots teachers, parents or aid workers may be unfamiliar with the academic term "social informatics," many already appreciate the implications of an interwoven relationship of technology and public organizations. Social informatics has recently given birth to "community informatics," which also considers unique aspects of the particular culture into which technology is placed, so that communities can most effectively use that technology to achieve social, economic, political or cultural goals.

A More Integrated Attempt

ONE EXAMPLE of a program based on a community informatics approach is the Gyandoot (which translates to "purveyor of knowledge") project in India. In 2000 in the southwest corner of Madhya Pradesh, one of India's poorest states, the government established this digital effort

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to bring more economic and political power to the rural population, nearly two thirds of whom are undernourished and illiterate. Each village received a computer kiosk, which is connected to the others in a network. Local entrepreneurs service the machines, and a small team hired by the government creates content for the Gyandoot intranet, based on an analysis of the people's social and economic needs.

This content includes updated prices of popular crops at the district, regional and national markets, so that small farmers can decide whether to harvest their crop and where to sell it, without wasting a day traveling to the district capital for price checks. A complaint service lets villagers report local problems, such as malfunctioning hand pumps or teachers failing to show up at schools. With villagers quickly able to voice such concerns digitally, government services have started to improve.

Local kiosk managers operate the computers, thus making the service, which costs a few cents per use, accessible even to the illiterate. Kiosk managers also offer computer training to village children for a small fee, thereby upping the collective computer skills of the community while affording additional income to the managers. And Gyandoot is used to connect with the area's broad socioeconomic initiatives, such as a "healthiest child" campaign, which provides information about vaccinations and nutrition.

Gyandoot was inexpensive to launch, because it involves only one computer per village, and it is partly self-sustaining, because kiosk operators are able to recover some of their costs through small fees to users. With its emphasis on meeting user needs through small-scale, locally run services, it has much in common with the earlier model of telephone kiosks that helped to extend phone access throughout much of India. In the nine months beginning in October 2001, the Gyandoot kiosks had some 21,300 users, 80 percent of whom had annual incomes of less than $300. The number of users is a small percentage of the population, but the benefits of the project, such as improved government services, eventually ripple outward to friends, families and co-workers.

The magnitude of the Gyandoot success story remains to be determined. But the underlying approach—a combination of well-planned and low-cost infusions of technology with content development and educational campaigns targeted to social development—is surely a healthy alternative to projects that rely on planting computers and waiting for something to grow.

The key issue is not unequal access to computers but rather the unequal ways that computers are used.

Fine-Tuning in California

A DOMESTIC CASE, which I investigated with doctoral candidate Jodie Wales, also shows the importance of the community informatics approach. California high schools offer Advanced Placement (AP) courses that give students college credit and facilitate their admission to the best universities. These courses are available in dramatically unequal numbers, however, largely in relation to the socioeconomic status and ethnicity of student populations. For example, in 1999 Beverly Hills High School, which is 9 percent African-American and Hispanic, offered 45 AP classes. Inglewood High School, in a different part of the same metropolitan area and with 97 percent black and Hispanic students, offered only three such courses.

To address this problem, in 2000 the University of California Office of the President and the university's College Preparatory Initiative engaged in a collaboration with the Anaheim Union High School District, which has a large Hispanic population. The first effort was an online AP course in macroeconomics, because many of their students, even the poorer of them, had some access to computers and the Internet outside of school. Attendees of several schools enrolled in the courses, thus potentially overcoming the problem of small and dispersed populations of advanced students. The result: only six of 22 students completed the course. Some reasons became clear through student surveys and interviews. The online instructional format—with students completing work independently from their home computers—lacked sufficient structure, teacher contact and peer interaction to maintain students' motivation to cope with the challenging material. The Hispanic students commented most frequently that they preferred these types of social support.

Still, the failure was fruitful. A revised program the next year brought students from several schools to a computer laboratory at a central location, this time to take an honors course, "Introduction to Computer Science and the C Programming Language." Although the class was still taught online to take advantage of the distant expert instructor and the computer-based curriculum, a local teacher joined the students to answer questions and provide general assistance. The combination of online expert instruction and face-to-face teacher and peer interaction proved much more effective: 56 of 65 students completed the course. Based on these results, the University of California College Preparatory Initiative abandoned the previous model of pure online instruction in exchange for the combined online and face-to-face model. (Of course, students may find an honors computer class somewhat more accessible than an AP macroeconomics course, or the former might be better suited for the online setting. Such points must also be considered

FARMERS ACCESS the Gyandoot intranet at a community computer facility in central India's Dhar district, where 60 percent of the 1.7 million residents live below the poverty line. The intranet provides crop prices, official application forms, and a place to hold village auctions and to air public grievances.

PABLO BARTHOLOMEW *Netphotograph.com*

when devising the mode of instruction.)

More and more evidence points to the need for a careful consideration of all potential ramifications before applying technology as an educational Band-Aid. In fact, my research—together with that of other educational investigators such as Henry J. Becker of the University of California at Irvine, Harold Wenglinsky of the City University of New York and Janet Schofield of the University of Pittsburgh—shows that computer use in schools is as likely to exacerbate inequality as lessen it. The key issue is not unequal access to computers but rather the unequal ways that computers are used. Our studies note that kindergarten through 12th grade students who enjoy a high socioeconomic status more frequently use computers for experimentation, research and critical inquiry, whereas poor students engage in less challenging drills and exercises that do not take full advantage of computer technology. In mathematics and English classes, where such drills are common, poor students actually have more access to computers than do more affluent ones. Only in science classes, which rely on experiments and simulations, do wealthy students use computers more. Once again, a "digital divide" framework that focuses on access issues alone fails to face these broader inequalities in technology use and learning.

Changing the Mind-set

PEOPLE ACCESS digital information in a wide variety of ways and usually as part of social networks involving relatives, friends and co-workers. Literacy provides a good analogy. Literacy does not exist in a bipolar divide between those who absolutely can and cannot read. There are levels of literacy for functional, vocational, civic, literary and scholarly purposes. And people become literate not just through physical access to books but through education, communication, work connections, family support and assistance from social networks. Similarly, technology can be well implemented to augment and improve existing social efforts and programs.

The bottom line is that there is no binary digital divide and no single overriding factor for determining—or closing—such a divide. Technology does not exist as an external variable to be injected from the outside to bring about certain results. It is woven into social systems and processes. And from a policy standpoint, the goal of bringing technology to marginalized groups is not merely to overcome a technological divide but instead to further a process of social inclusion. Realizing this objective involves not only providing computers and Internet links or shifting to online platforms but also developing relevant content in diverse languages, promoting literacy and education, and mobilizing community and institutional support toward achieving community goals. Technology then becomes a means, and often a powerful one, rather than an end in itself.

It is important to note that the Bush administration is cutting funding of programs that foster access to technology. Some might argue that such cuts are appropriate if there is no digital divide, but that reasoning is as specious as simplistic solutions based on the notion of a divide. The opposite of divide is *multiply*. Policy planners should stop thinking in terms of divides to be bridged. The combination of carefully planned infusions of technology with relevant content, improved education and enhanced social support can multiply those assets that communities already have. SA

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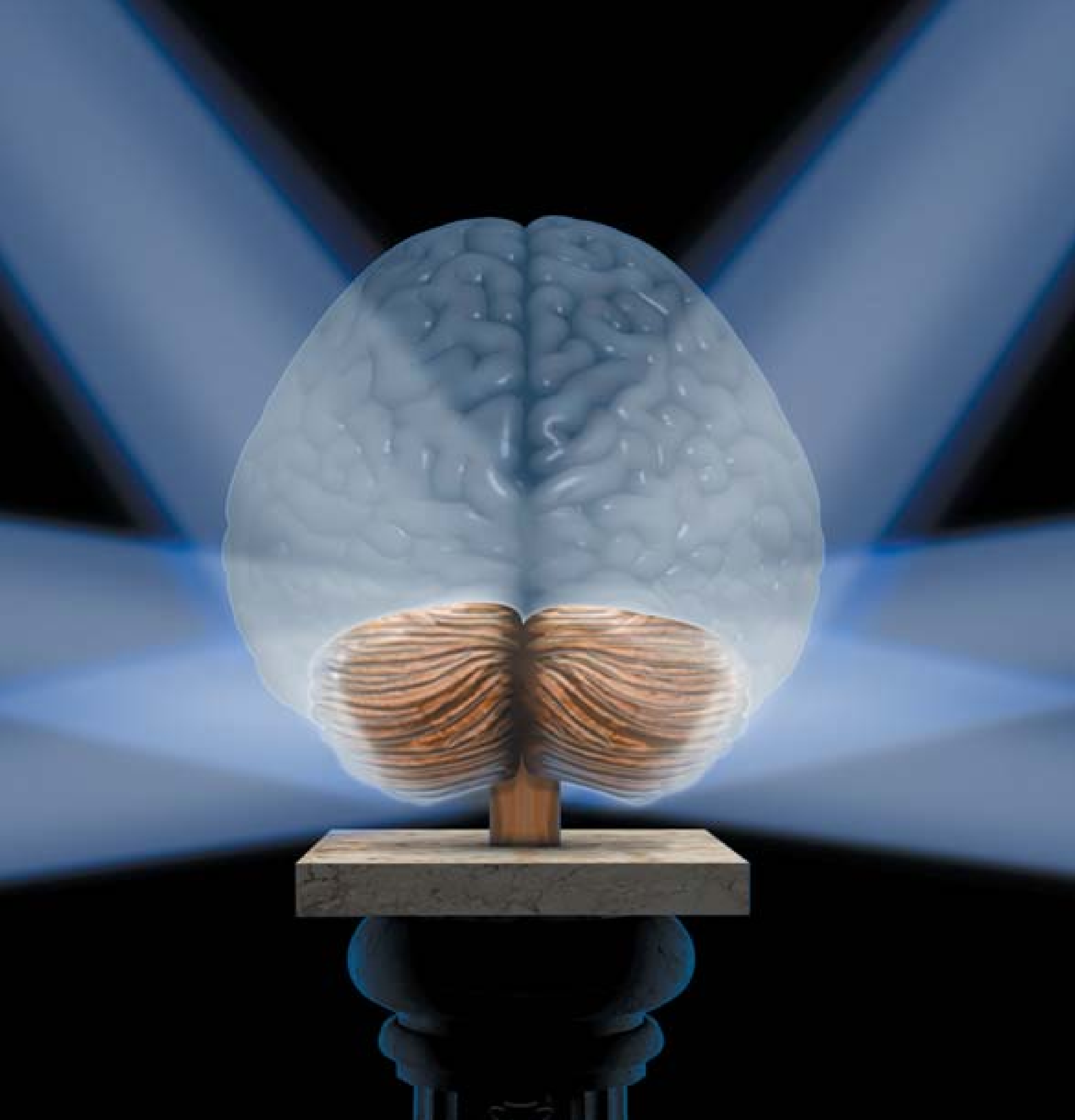
Athena Alliance: **www.athenaalliance.org/**

Center for Social Informatics: **www.slis.indiana.edu/CSI/**

Community Informatics Research and Applications Unit: **www.cira.org.uk/**

Community Technology Centers Network: **www.ctcnet.org**

Digital Divide Network: **www.digitaldividenetwork.org/**



Long thought to be solely the BRAIN'S COORDINATOR of body movement, THE CEREBELLUM is now known to be active during a wide variety of cognitive and perceptual activities

Rethinking the "Lesser Brain"

By James M. Bower and Lawrence M. Parsons

"In the back of our skulls, perched upon the brain stem under the overarching mantle of the great hemispheres of the cerebrum, is a baseball-sized, bean-shaped lump of gray and white brain tissue. This is the cerebellum, the 'lesser brain.'"

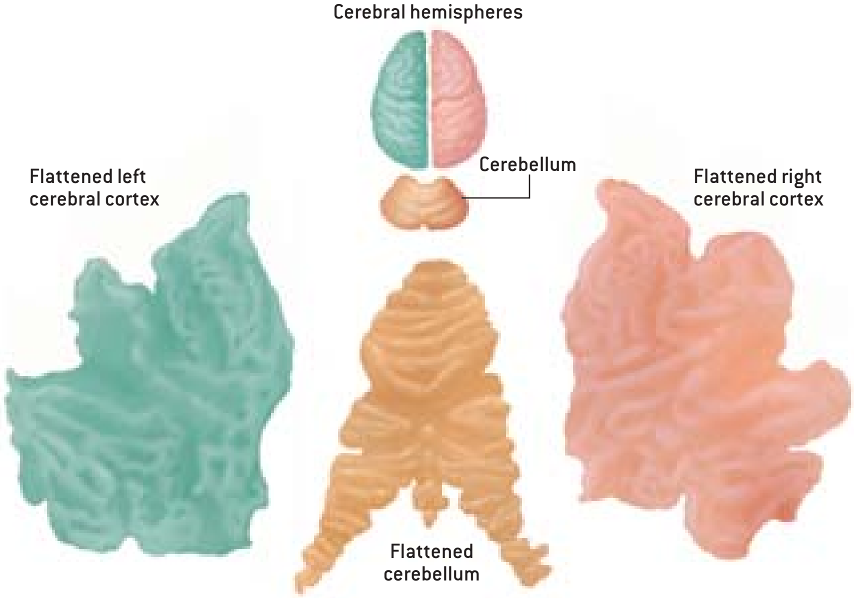
So began, somewhat modestly, the article that in 1958 introduced the cerebellum to the readers of *Scientific American*. Written by Ray S. Snider of Northwestern University, the introduction continued, "In contrast to the cerebrum, where men have sought and found the centers of so many vital mental activities, the cerebellum remains a region of subtle and tantalizing mystery, its function hidden from investigators." But by the time the second *Scientific American* article on the cerebellum appeared 17 years later, author Rodolfo R. Llinás (currently at New York University Medical Center) confidently stated, "There is no longer any doubt that the cerebellum is a central control point for the organization of movement."

Recently, however, the cerebellum's function has again become a subject of debate. In particular, cognitive neuroscientists using powerful new tools of brain imaging have found that the human cerebellum is active during a wide range of activities that are not directly related to movement. Sophisticated cognitive studies have also revealed that damage to specific areas of the cerebellum can cause unanticipated impairments in nonmotor processes, especially in how quickly and accurately people perceive sensory information. Other findings indicate that the cerebellum may play important roles in short-term memory, attention, impulse control, emotion, higher cognition, the ability to schedule and plan tasks, and possibly even in conditions such as schizophrenia and autism. Additional neurobiological experiments—both on the pattern of sensory inputs to the cerebellum and on the ways in which the cerebellum processes that information—also suggest a need to substantially revise current thinking about the function of this organ. The cerebellum has once again become an area of "tantalizing mystery."

FRANK IPPOLITO

LARGER THAN YOU'D THINK

FLATTENING the outer layer, or cortex, of the two human cerebral hemispheres and the cerebellum illustrates that the cerebellum has roughly the same surface area as a single cerebral hemisphere, even though when folded it takes up much less space. The size and complexity of the cerebellum indicate that it must play a crucial function.



In retrospect, it is perhaps not surprising that the cerebellum acts as more than just a simple controller of movement. Its great bulk and intricate structure imply that it has a more pervasive and complex role. It is second in size only to the cerebral cortex, the wrinkled surface of the brain's two large hemispheres, which is known to be the seat of many critical brain functions. Like the human cerebral cortex, the cerebellum packs a prodigious amount of circuitry into a small space by folding in on itself numerous times. Indeed, the human cerebellum is much more folded than the cerebral cortex; in various mammals, it is the sole folded brain structure. Flattening out the human cerebellum yields a sheet with an average area of 1,128 square centimeters—slightly larger than a record album cover. That is more than half the 1,900 square centimeters of the surface area of the two cerebral cortices added together.

The cerebellum clearly has an important job, because it has persisted—and become larger—during the course of evolution. Although biologists often consider the growth of the cerebral cortex to be the defining characteristic of human brain evolution, the cerebellum has also enlarged significantly, increasing in size at least three times during the past million years of human history, according to fossilized skulls. Perhaps the cerebellum's most remarkable feature, however, is that it contains more individual nerve cells, or neurons, than the rest of the brain combined. Furthermore, the way those neurons are wired together has remained essentially constant over more than 400 million years of vertebrate evolution [*see box on opposite page*]. Thus, a shark's cerebellum has neurons that are organized into circuits nearly identical to those of a person's.

More than Movement

THE HYPOTHESIS that the cerebellum controls movement was first proposed by medical physiologists in the middle of the 19th century, who observed that removing the cerebellum could result in immediate difficulties in coordinating movement. During World War I, English neurologist Gordon Holmes added great detail to these early findings by going from tent to tent on the front lines of battle and documenting the lack of motor coordination in soldiers who had suffered gunshot or shrapnel wounds to the cerebellum.

In the past 15 years, however, more refined testing techniques have made the story more complicated. In 1989 Richard B. Ivry and Steven W. Keele of the University of Oregon observed that patients with cerebellar injuries cannot accurately judge the duration of a particular sound or the amount of time that elapses between two sounds. In the early 1990s researchers led by Julie A. Fiez of Washington University observed that patients with damage to the cerebellum were more error-prone than others in performing certain verbal tasks. One such individual, for instance, required additional time to think of an appropriate verb, such as "to shave," when shown a picture of a razor, for example. He came up with a descriptor such as "sharp" more readily.

In more recent studies, the two of us demonstrated that patients who have neurodegenerative diseases that specifically shrink the cerebellum are often less accurate than others in judging fine differences between the pitch of two tones.

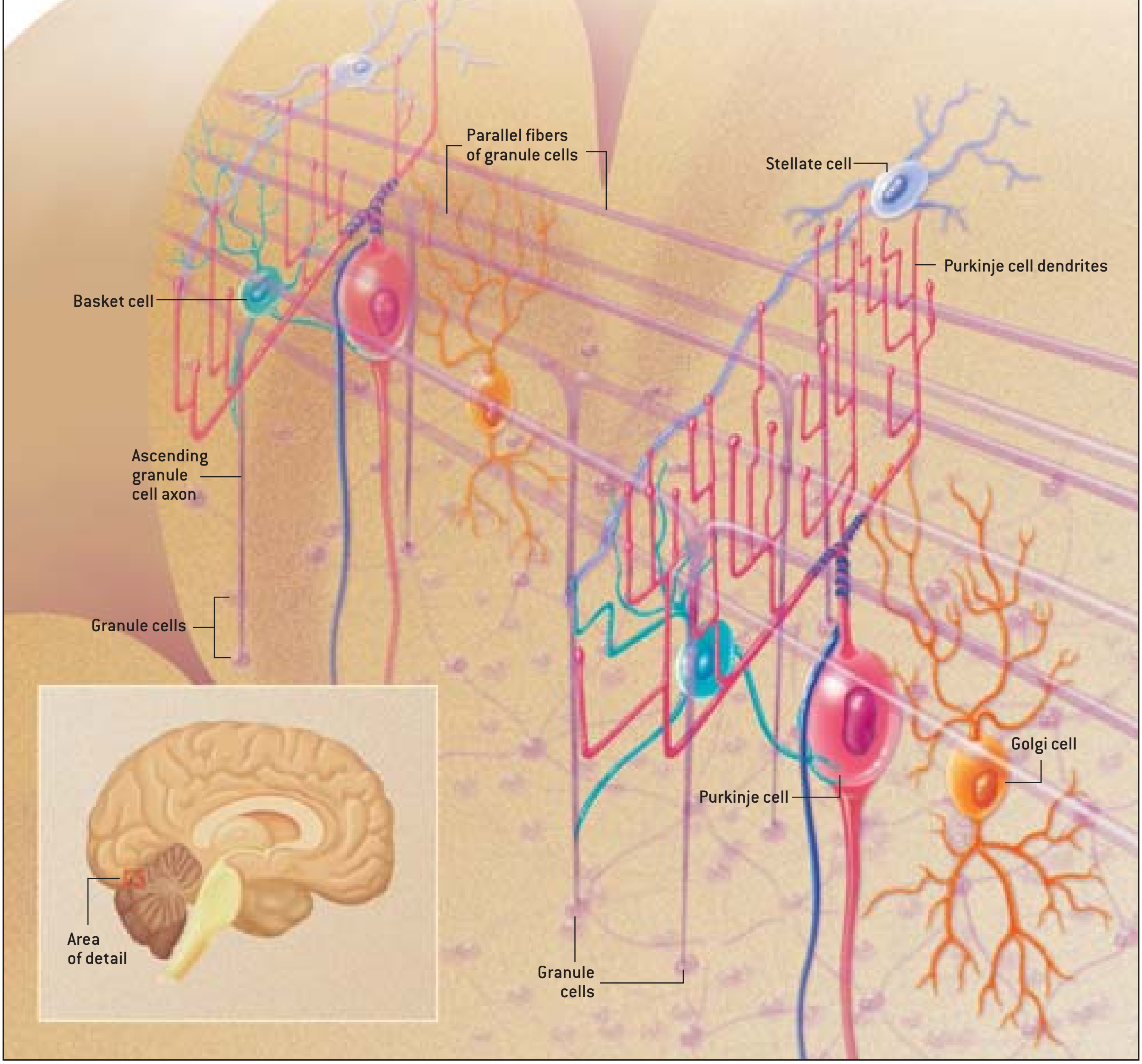
Overview/*The Cerebellum*

- The cerebellum sits at the base of the brain and has a complex neural circuitry that has remained virtually the same throughout the evolution of animals with backbones.
- The traditional notion that the cerebellum controls movement is being questioned by studies indicating that it is active during a wide variety of tasks. The cerebellum may be more involved in coordinating sensory input than in motor output.
- Removing the cerebellum from young individuals often causes few obvious behavioral difficulties, suggesting that the rest of the brain can learn to function without a cerebellum.

ALICE Y. CHEN; SOURCE: DAVID C. VAN ESSEN *Washington University School of Medicine*

HOW THE CEREBELLUM IS WIRED

THE BASIC FEATURES of cerebellar circuitry have been known since the seminal work of Spanish neuroanatomist Santiago Ramón y Cajal in the late 1800s. The central neuron is the Purkinje cell, named for Czech physiologist Johannes E. Purkinje, who identified it in 1837. The Purkinje cell provides the sole output of the cerebellar cortex and is one of the largest neurons in the nervous system, receiving an extraordinary 150,000 to 200,000 inputs (synapses)—an order of magnitude more than any single neuron in the cerebral cortex. These inputs spring principally from one of the smallest vertebrate neurons, the cerebellar granule cell. Granule cells are packed together at a density of six million per square millimeter, making them the most numerous type of neuron in the brain. The axon, or main trunk line carrying the outgoing signal, of every granule cell rises vertically out of the granule cell layer, making multiple inputs with its overlying Purkinje cell. The axon then splits into two segments that stretch away in opposite directions. These segments align into parallel fibers that run through the arms, or dendrites, of a Purkinje cell like wires through an electrical pole, providing a single input to many hundreds of Purkinje cells. Granule cells also communicate with three other types of neurons—the stellate, basket and Golgi cells—which help to modulate the signals emitted by both the granule and Purkinje cells. This basic pattern occurs in every cerebellum, indicating that it must be integral to its function. *—J.M.B. and L.M.P.*



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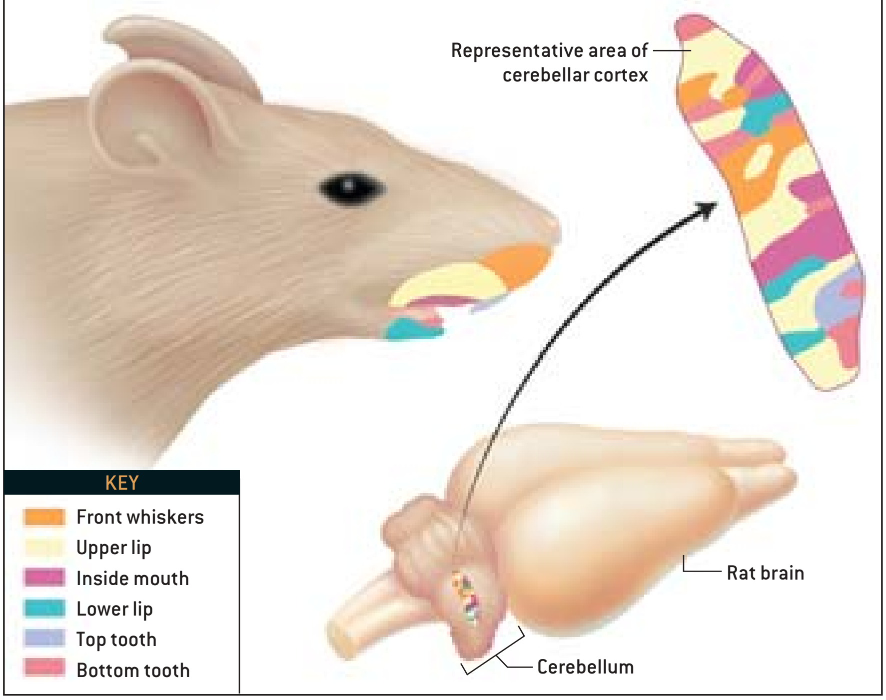
Similarly, Peter Thier of the University of Tübingen in Germany and his co-workers found that people with damage to, or shrinkage of, part or all of the cerebellum are prone to make errors in tests in which they are asked to detect the presence, speed and direction of moving patterns. In addition, Hermann Ackermann and his collaborators, also at Tübingen, observed that patients with degenerated cerebellums are less able than healthy persons to discriminate between the similar-sounding words "rabbit" and "rapid."

The impairments experienced by people with cerebellar damage can extend beyond language, vision and hearing. Jeremy D. Schmahmann of Massachusetts General Hospital reported that adult and child cerebellar patients have difficulty modulating their emotions: they either fail to react to or overreact to a stimulus that elicits a more moderate response from most people. Other researchers have demonstrated that adults with cerebellar damage show delays and tend to make mistakes in spatial reasoning tests, such as determining whether the shapes of objects seen from different views match. Some scientists have also tied the cerebellum to dyslexia. Rod I. Nicolson and his colleagues at the University of Sheffield in England, for instance, found that people with dyslexia and those with cerebellar damage have similar deficits in learning ability and that dyslexics have reduced cerebellar activity during certain tasks.

Other recent studies suggest that the cerebellum might be involved in working memory, attention, mental functions such as planning and scheduling, and impulse control. In 1992 Jordan Grafman and his co-workers at the National Institutes of Health observed, for instance, that individuals with an atrophied cerebellum had trouble with the planning and scheduling of steps required to solve the Tower of Hanoi problem, in which rings of different sizes must be arranged on a series of pegs according to specific rules. Two independent neuroimaging studies conducted in 1997 reported that the cerebellum of healthy volunteers became active when they were asked to recall a list of letters they had heard recited moments earlier or when they were instructed to search a pattern for a specific image. In 2002 a brain imaging study by Xavier Castellanos, Judith L. Rapoport and their colleagues at the National Institute of Mental Health found that the cerebellum of children with attention-deficit hyperactivity disorder—which is characterized by a lack of impulse control—is reduced in size. Finally, brain imaging studies of healthy people and animals indicate that the cerebellum is normally active during sensory processes such as hearing, smell, thirst, need for food or air, awareness of body movement, and perception of pain.

THE CEREBELLUM'S FRACTURED NATURE

A PARTICULAR AREA on a rat's face is not represented as a single area in the cerebellum. When scientists use a probe to touch a rat's lower lip, for instance, they can record electrical activity at several widely spaced spots on the animal's cerebellar cortex. Such fragmentation may allow the cerebellum to integrate a variety of incoming sensory information obtained by different body parts during the course of exploration.



THE AUTHORS

JAMES M. BOWER and *LAWRENCE M. PARSONS* are both at the Research Imaging Center at the University of Texas Health Science Center in San Antonio, where Bower is professor of computational neurobiology and Parsons is professor of cognitive neuroscience. Bower—who is also professor at the Cajal Neuroscience Center at the University of Texas at San Antonio—is a founder of the *Journal of Computational Neuroscience* and of the international Annual Computational Neuroscience Meeting. He has also had a long-standing involvement in science education and is one of the creators of a children's educational Web site (Whyville.net). Parsons has been responsible for establishing a cognitive neuroscience program at the National Science Foundation. He is a founding member of the editorial board of the journal *Human Brain Mapping* and serves as a trustee for the International Foundation for Music Research.

Touching, Feeling

WE ARE AMONG the researchers who have become convinced that the traditional motor-control theory of cerebellar function is inadequate to account for the new data. We came to this conclusion initially by intensively studying cerebellar re-

ALICE Y. CHEN

gions that are active during touch. One of us (Bower) began such work while a graduate student more than 20 years ago in the laboratory of Wallace I. Welker at the University of Wisconsin–Madison. These investigations used a technique called micromapping to record the electrical activity of small patches of neurons in the brains of rats as they were touched lightly on various parts of their bodies.

Such tactile stimuli evoked activity across a large area of the cerebellum [*see illustration on opposite page*]. What is more, the map appeared fractured, with neighboring areas of the cerebellum often receiving inputs from disparate regions of the body and with areas that were far apart being represented next to one another in the cerebellum. Such a mapping plan is very different from that occurring in the cerebral cortex, where the spatial relations between areas of the body surface are retained in the cortical regions that respond to and send signals to those areas.

Although the fractured nature of the cerebellar maps is unusual, an even more surprising finding was that the rat cerebellum receives input primarily from the face of the animal. This was initially confusing because Snider had shown earlier that most of the tactile region of the cat cerebellum receives input from the forepaws and that the bulk of that region in monkeys is active when the fingers are touched.

The cerebellum is more involved in SENSORY than in PURE MOTOR FUNCTION.

A Sensory Coordinator

GIVEN THE DIFFERENCES in the regions of the body surface represented in the cerebellum of various types of animals, the question became: How is the mouth of a rat like the forepaws of a cat or the fingers of a monkey? The conclusion from the Wisconsin studies appeared to be that each structure is used by each animal to learn about its environment through touch. Anyone with a cat knows how much mischief its paws can cause, and anyone familiar with children recognizes how actively—and sometimes painfully—little fingers are used to gain information about the youngsters' immediate world. But rats tend to get into trouble using their mouths. The fractured structure of the touch maps in the cerebellum supported the idea that the region was somehow comparing the sensory data coming from the multiple body parts used by each animal to explore its world. These maps seemed to be organized according to the use of the body parts rather than on their absolute proximity on the body surface. The idea that the rat cerebellum was somehow comparing the sensory information coming from different parts of the face was further supported by models and experiments examining how the cerebellum responded to these inputs. What emerged was a new hypothesis of cerebellar function suggesting that the cerebellum was specifically involved in coordinating the brain's acquisition of sensory data.

Although proposing novel ideas of brain function is easy, having the ideas accepted in a field that had decided in the 1850s that the cerebellum was a motor structure is a different story. In this case, the task was made even harder by the fact that there is clearly an extremely close linkage between sensory and motor systems in the brain, especially those involving touch. To make sure that we were seeing the effects of only sensory—and not motor—activity, we needed to study people, who, unlike rats, can follow explicit instructions about when to move and when not to. It was at this point that the partnership between the two of us began. In collaboration with Peter T. Fox of the University of Texas

CHRIS HARTLOVE

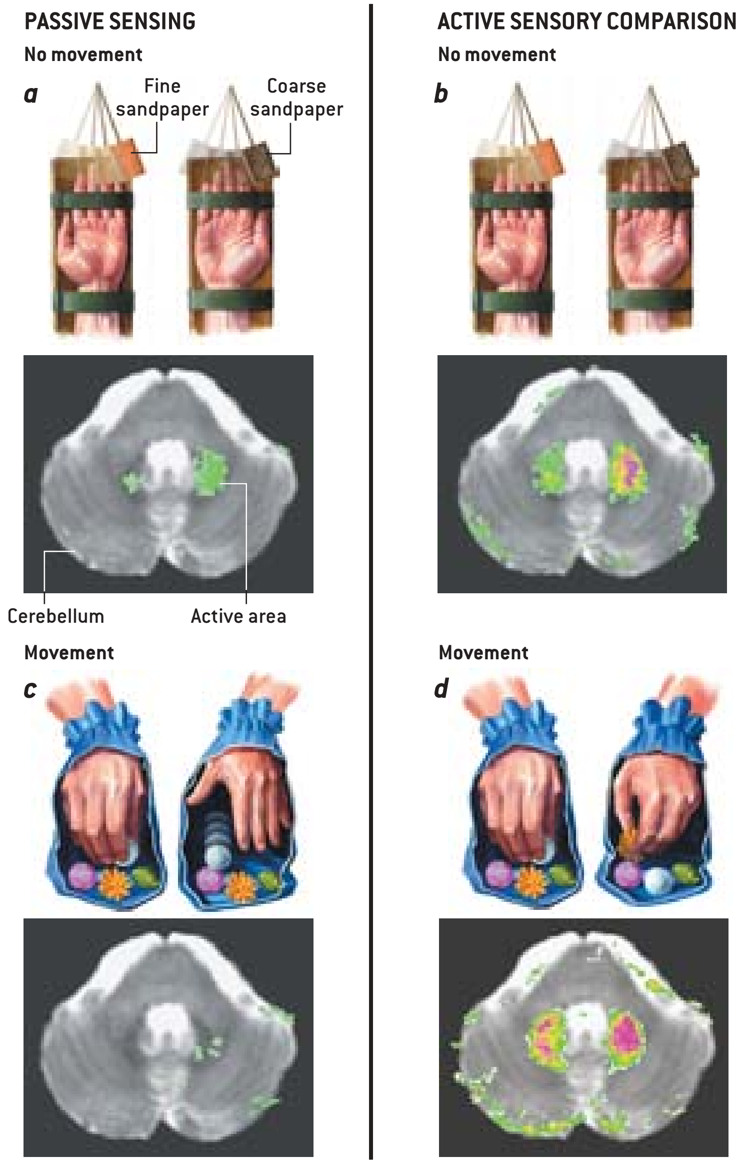
RUDOLF VAN'T HOFF of Howard County, Maryland, has cerebellar damage caused by type 1 spinocerebellar atrophy, a rare genetic disease that usually manifests itself in middle age. The disorder has affected van't Hoff's balance, speech, and coordination and has also impaired his ability to discriminate between some sounds. He steadies his body with a bungee cord when sitting on his tractor.

PROBING CEREBELLAR FUNCTION

TO DISCRIMINATE BETWEEN the cerebellum's possible roles in coordinating movement and integrating sensory input, we devised a four-part experiment. We used a technique called functional magnetic resonance imaging to reveal brain activity in the cerebellum of six healthy people while they were either sensing a stimulus on their fingers without moving them or picking up and dropping small objects. In the first scenario, we immobilized a subject's hands and rubbed pieces of sandpaper gently across their fingertips (*a*). Sometimes they were asked to compare the coarseness of two different types of sandpaper (*b*). Both were purely sensory tasks, but the latter one required each person to discriminate between what they were feeling on each hand.

The second scenario involved both sensory and motor aspects. A volunteer placed his or her hands into separate bags that contained small wooden balls of different shapes and textures. In the first task (*c*), the person was told to randomly pick up and drop the balls, paying little heed to their shapes. In the second task (*d*), the individual was asked to compare the shape and feel of two balls every time he or she picked one up in each hand.

The cerebellum showed very little activity during the task that simply required picking up and dropping balls (*c*). In general, it was most active when the subjects were evaluating what they were sensing, either while moving (*d*) or still (*b*). These findings and others support our hypothesis that the cerebellum's main role is in processing sensory information rather than in controlling movement. *—J.M.B. and L.M.P.*



Health Science Center in San Antonio, we designed a neuroimaging study to compare the amount of cerebellar activity induced when volunteers were instructed to use their fingers for a sensory touch discrimination task or told just to pick up and drop small objects. Under all previous theories of cerebellar function, the fine finger motor control required in picking up and dropping the small objects would be predicted to induce large amounts of cerebellar activity in the area associated with touch. Instead we found very little cerebellar activity in that region during the pick-up-and-drop task, whereas sensory exploration using the fingers caused an intense cerebellar response [*see box above*]. This observation added support to our idea that the cerebellum is more involved in sensory than pure motor function and in particular that it is highly active during the process of acquiring sensory data.

Life without a Cerebellum

OUR SENSORY-ACQUISITION hypothesis is but one of several new theories arising as a consequence of the growing evidence for cerebellar involvement in more than just motor control. In many cases, the new data have been accommodated by simply broadening existing motor theories to account for nonmotor results. Ivry, for instance, has advocated a "generalized timing" hypothesis of cerebellar function that suggests that the cerebellum controls the timing of body movements (such as coordinating changes in joint angles) to allow individuals to time the duration of sensory inputs such as sights and sounds.

Other researchers have posited that the cerebellum not only facilitates fine

MATT COLLINS (*illustrations*); REPRINTED FROM JIA-HONG GAO ET AL. IN *SCIENCE*, VOL. 272; APRIL 26, 1996 (*brain scans*) movement but also "smooths" the processing of information related to mood and thought. Schmahmann expressed such a view in 1991, and in 1996 Nancy C. Andreason of the University of Iowa adapted the hypothesis to schizophrenia. She maintains that cerebellar deficits could underlie the disordered mental function characteristic of the disease. Other scientists have proposed that the regions of the cerebellum that have expanded dramatically during human evolution provide computational support for psychological tasks that can be offloaded from the cerebral cortex when it is overburdened.

As the number of conditions that involve changes in cerebellar activity has grown, researchers have attributed more and more functions to the cerebellum. But scientists must yet explain how a single brain structure whose neural circuitry is organized into a uniform, repetitive pattern can play such an integral role in so many disparate functions and behaviors.

What is even more confounding is that people can recover from cerebellar injury. Although total removal of the cerebellum initially disrupts movement coordination, individuals (particularly young ones) can, with sufficient time, regain normal function to a considerable degree. Such plasticity is a general characteristic of the brain, but similar damage to primary sensory or motor-control regions of the cerebral cortex usually leaves animals and humans severely and permanently impaired in specific functions.

The capacity to recover from removal of the cerebellum has led some researchers to propose facetiously that its function might be to compensate for its own absence. It is highly unlikely, however, that such a large and intricate structure as the cerebellum is functionless or vestigial. Instead cerebellar function appears to permit the rest of the brain to compensate to a considerable degree for its absence.

Few cerebellar theories, including those based on motor control, have provided an explanation for this puzzling resilience. In our view, the ability of the brain to compensate for the cerebellum's absence implies a general and subtle support function. Under the sensory coordination hypothesis we favor, the cerebellum is not responsible for any particular overt behavior or psychological process. Rather it functions as a support structure for the rest of the brain. That support involves monitoring incoming sensory data and making continuous, very fine adjustments in how that information is acquired—the objective being to assure the highest possible quality of sensory input.

We predict that those adjustments take the form of extremely subtle changes in the positions of probing human fingers or rat whiskers or in the retina or the inner ear. As a support structure, the cerebellum would be expected to have some level of activity in a large number of conditions, especially those requiring careful control of incoming and perhaps remembered sensory data. Other brain systems can usually compensate for the lack of sensory data coordination through the use of alternative processing strategies if the cerebellum is damaged or removed.

Indeed, motor coordination studies suggest that people with cerebellar damage slow down and simplify their movements—reasonable strategies to compensate for a lack of high-quality sensory data. An interesting and important extension of this idea is that the continued operation of a faulty cerebellum would have more serious consequences than its complete removal. Although other brain structures can compensate for the outright lack of sensory data control, ongoing faulty control would be expected to cause continuing dysfunction in other brain regions attempting to use bad data. This type of effect might explain the recent implications for cerebellar involvement in disorders such as autism, in which patients fail to respond to incoming sensory data.

Hypotheses such as ours carry a useful reminder for future research: the presence of activity in a brain area does not necessarily mean that it is directly involved in a particular behavior or psychological process. Most of the machinery under the hood of a car, by analogy, is there to support the function of the engine. One could generate all kinds of hypotheses about the role of the radiator in propulsion—by correlating increased temperature to miles per hour, for instance, or by observing that a car ceases to run if its radiator is removed. But the radiator is not the engine.

If the cerebellum is primarily a support structure, then it does not contribute directly to motor coordination, memory, perception, attention, spatial reasoning or any of the many other functions recently proposed. Although this theory is one of several competing to account for the new and surprising data about the cerebellum, it is clear that how we think about this brain structure—and therefore how we conceive of the brain as a whole—is about to change. SA

It is clear that how we think about this brain structure—and how we CONCEIVE OF THE BRAIN as a whole—is about to change.

MORE TO EXPLORE

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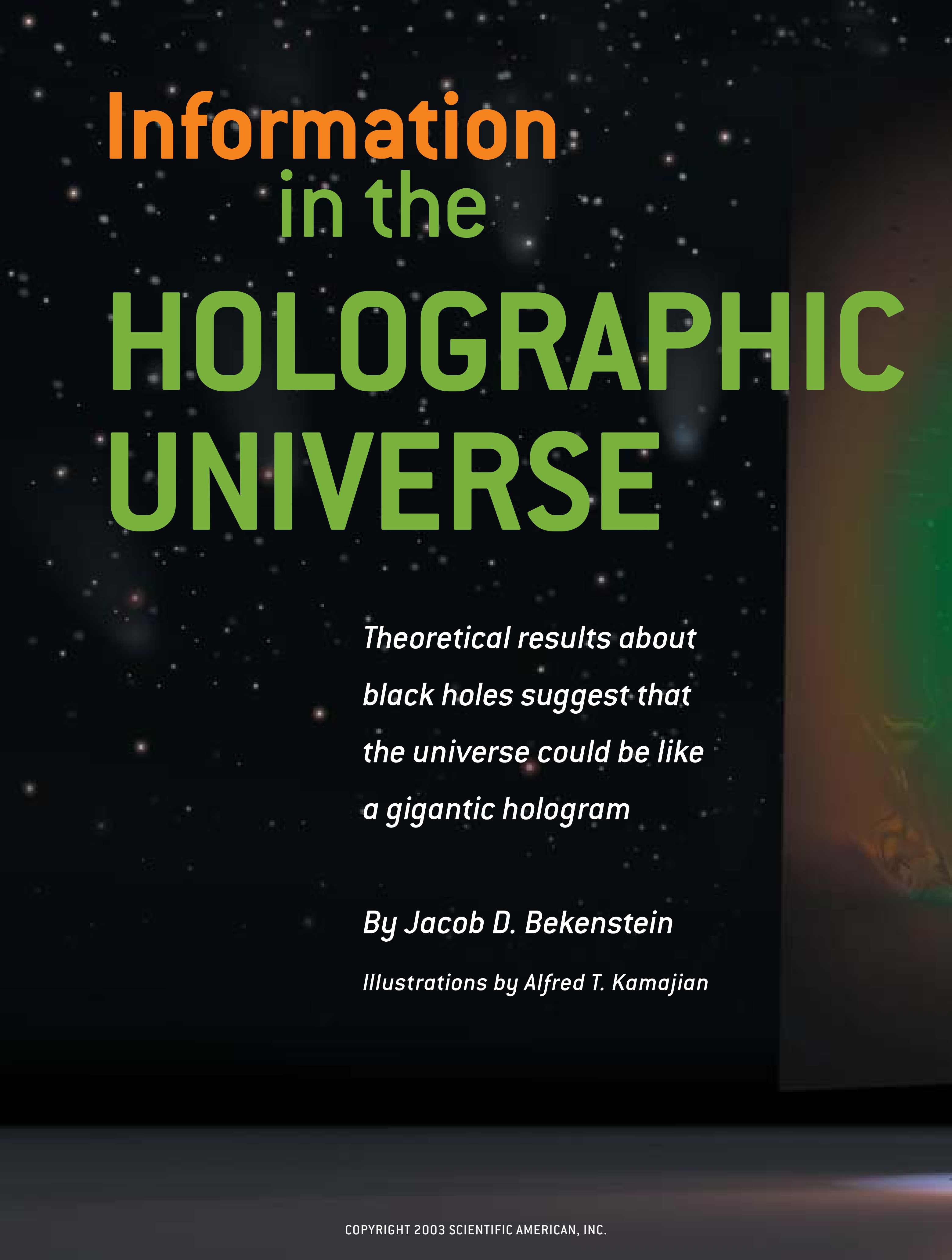
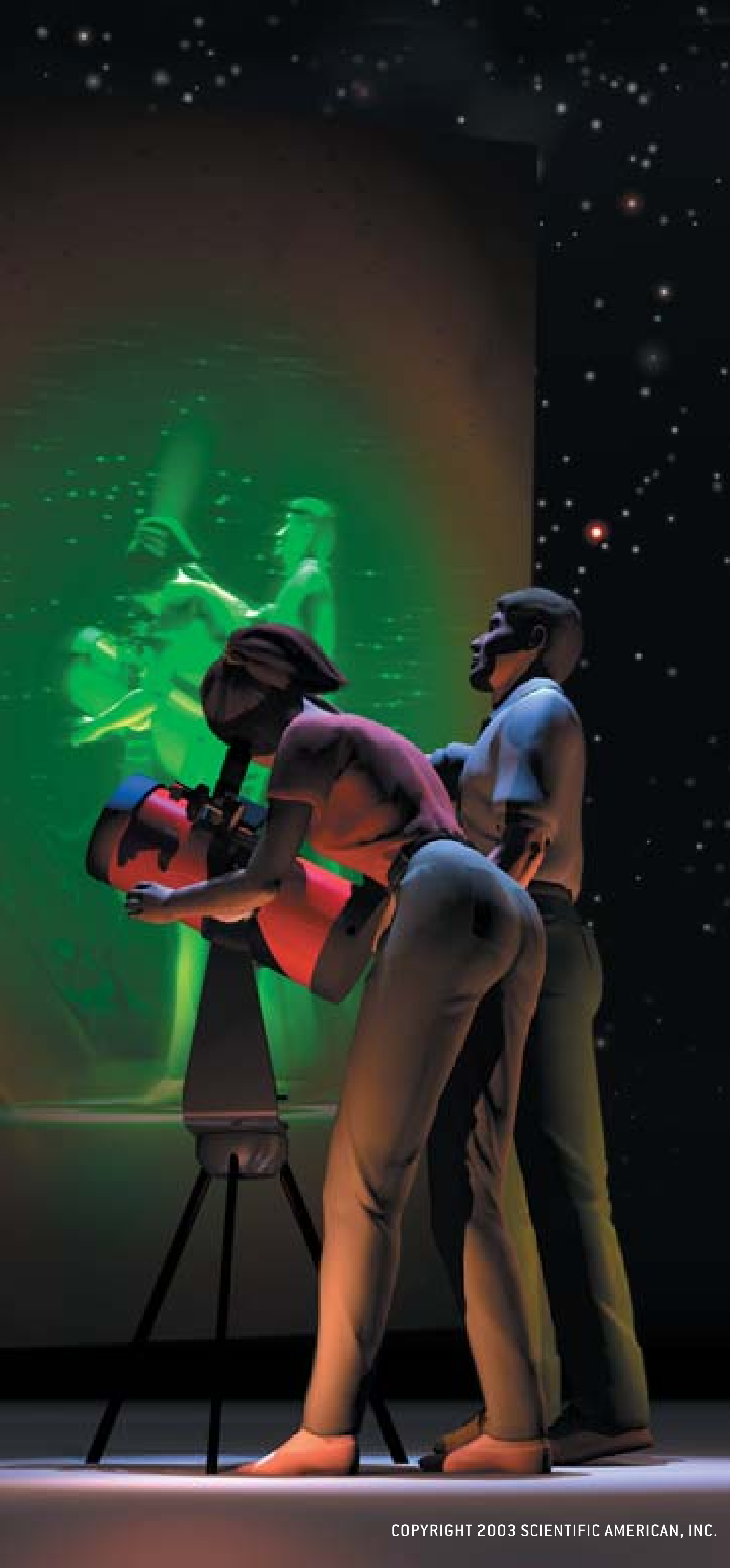


Information in the HOLOGRAPHIC UNIVERSE

Theoretical results about black holes suggest that the universe could be like a gigantic hologram

By Jacob D. Bekenstein

Illustrations by Alfred T. Kamajian



Ask anybody what the physical world is made of, and you are likely to be told "matter and energy."

Yet if we have learned anything from engineering, biology and physics, information is just as crucial an ingredient. The robot at the automobile factory is supplied with metal and plastic but can make nothing useful without copious instructions telling it which part to weld to what and so on. A ribosome in a cell in your body is supplied with amino acid building blocks and is powered by energy released by the conversion of ATP to ADP, but it can synthesize no proteins without the information brought to it from the DNA in the cell's nucleus. Likewise, a century of developments in physics has taught us that information is a crucial player in physical systems and processes. Indeed, a current trend, initiated by John A. Wheeler of Princeton University, is to regard the physical world as made of information, with energy and matter as incidentals.

This viewpoint invites a new look at venerable questions. The information storage capacity of devices such as hard disk drives has been increasing by leaps and bounds. When will such progress halt? What is the ultimate information capacity of a device that weighs, say, less than a gram and can fit inside a cubic centimeter (roughly the size of a computer chip)? How much information does it take to describe a whole universe? Could that description fit in a computer's memory? Could we, as William Blake memorably penned, "see the world in a grain of sand," or is that idea no more than poetic license?

Remarkably, recent developments in theoretical physics answer some of these questions, and the answers might be important clues to the ultimate theory of reality. By studying the mysterious properties of black holes, physicists have deduced absolute limits on how much information a region of space or a quantity of matter and energy can hold. Related results suggest that our universe, which we perceive to have three spatial dimensions, might instead be "written" on a two-dimensional surface, like a hologram. Our everyday perceptions of the world as three-dimensional would then be either a profound illusion or merely one of two alternative ways of viewing reality. A grain of sand may not encompass our world, but a flat screen might.

A Tale of Two Entropies

FORMAL INFORMATION theory originated in seminal 1948 papers by American applied mathematician Claude E. Shannon, who introduced today's most widely used measure of information content: entropy. Entropy had long been a central concept of thermodynamics, the branch of physics dealing with heat. Thermodynamic entropy is popularly described as the disorder in a physical system. In 1877 Austrian physicist Ludwig Boltzmann characterized it more precisely in terms of the number of distinct microscopic states that the particles composing a chunk of matter could be in while still looking like the same macroscopic chunk of matter. For example, for the air in the room around you, one would count all the ways that the individual gas molecules could be distributed in the room and all the ways they could be moving.

When Shannon cast about for a way to quantify the information contained in, say, a message, he was led by logic to a formula with the same form as Boltzmann's. The Shannon entropy of a message is the number of binary digits, or bits, needed to encode it. Shannon's entropy does not enlighten us about the value of information, which is highly dependent on context. Yet as an objective measure of quantity of information, it has been enormously useful in science and technology. For instance, the design of every modern communications device—from cellular phones to modems to compact-disc players—relies on Shannon entropy.

Thermodynamic entropy and Shannon entropy are conceptually equivalent: the number of arrangements that are counted by Boltzmann entropy reflects the amount of Shannon information one would need to implement any particular arrangement. The two entropies have two salient differences, though. First, the thermodynamic entropy used by a chemist or a refrigeration engineer is expressed in units of energy divided by temperature, whereas the Shannon entropy used by a communications engineer is in bits, essentially dimensionless. That difference is merely a matter of convention.

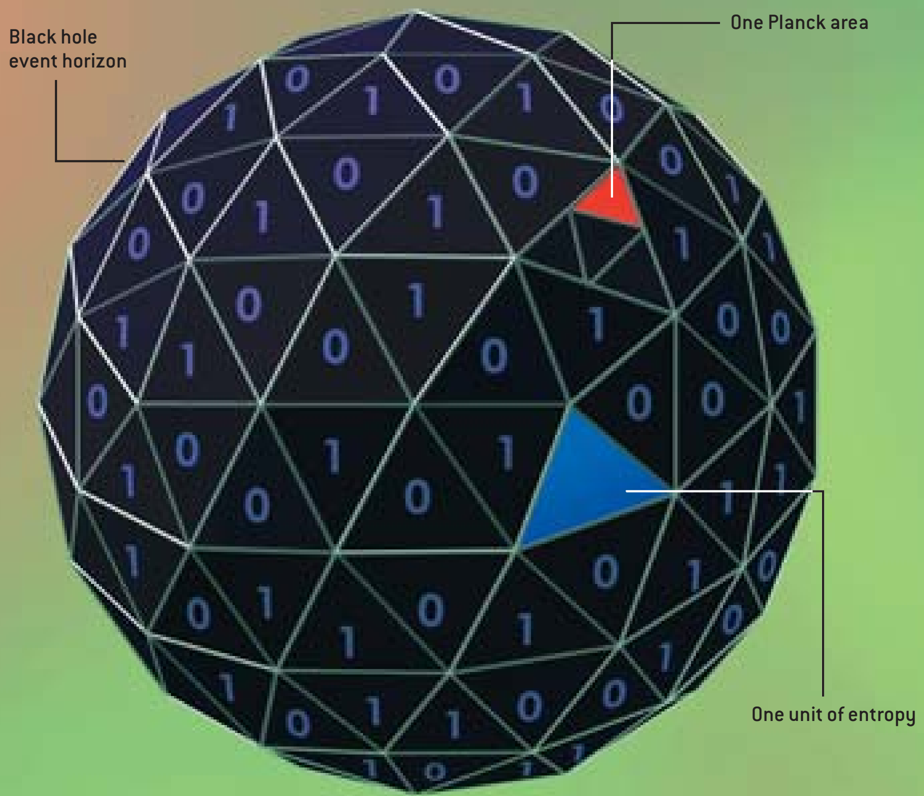
Even when reduced to common units, however, typical values of the two entropies differ vastly in magnitude. A silicon microchip carrying a gigabyte of data, for instance, has a Shannon entropy of about 10^{10} bits (one byte is eight bits), tremendously smaller than the chip's thermodynamic entropy, which is about 10^{23} bits at room temperature. This discrepancy occurs because the entropies are computed for different degrees of freedom. A degree of freedom is any quantity that can vary, such as a coordinate specifying a particle's location or one component of its velocity. The Shannon entropy of the chip cares only about the overall state of each tiny transistor etched in the silicon crystal—the transistor is on or off; it is a 0 or a 1—a single binary degree of freedom. Thermodynamic entropy, in contrast, depends on the states of all the billions of atoms (and their roaming electrons) that make up each transistor. As miniaturization brings closer the day when each atom will store one bit of information for us, the useful Shannon entropy of the state-of-the-art microchip will edge closer in magnitude to its material's thermodynamic entropy. When the two entropies are calculated for the same degrees of freedom, they are equal.

What are the ultimate degrees of freedom? Atoms, after all, are made of electrons and nuclei, nuclei are agglomerations of protons and neutrons, and those in turn are composed of quarks. Many physicists today consider electrons and quarks to be excitations of superstrings, which they hypothesize to be the most fundamental entities. But the vicissitudes of a century of revelations in physics warn us not to be dogmatic. There could be more levels of structure in our universe than are dreamt of in today's physics.

One cannot calculate the ultimate information capacity of a chunk of matter or, equivalently, its true thermodynamic entropy, without knowing the nature of the ultimate constituents of matter or of the deepest level of structure, which I shall refer to as level X. (This ambiguity causes no problems in analyzing practical thermodynamics, such as that of car

Overview/*The World as a Hologram*

- An astonishing theory called the holographic principle holds that the universe is like a hologram: just as a trick of light allows a fully three-dimensional image to be recorded on a flat piece of film, our seemingly three-dimensional universe could be completely equivalent to alternative quantum fields and physical laws "painted" on a distant, vast surface.
- The physics of black holes—immensely dense concentrations of mass—provides a hint that the principle might be true. Studies of black holes show that, although it defies common sense, the maximum entropy or information content of any region of space is defined not by its volume but by its surface area.
- Physicists hope that this surprising finding is a clue to the ultimate theory of reality.



THE ENTROPY OF A BLACK HOLE is proportional to the area of its event horizon, the surface within which even light cannot escape the gravity of the hole. Specifically, a hole with a horizon spanning A Planck areas has $A/4$ units of entropy. (The Planck area, approximately 10^{-66} square centimeter, is the fundamental quantum unit of area determined by the strength of gravity, the speed of light and the size of quanta.) Considered as information, it is as if the entropy were written on the event horizon, with each bit (each digital 1 or 0) corresponding to four Planck areas.

engines, for example, because the quarks within the atoms can be ignored—they do not change their states under the relatively benign conditions in the engine.) Given the dizzying progress in miniaturization, one can playfully contemplate a day when quarks will serve to store information, one bit apiece perhaps. How much information would then fit into our one-centimeter cube? And how much if we harness superstrings or even deeper, yet undreamt of levels? Surprisingly, developments in gravitation physics in the past three decades have supplied some clear answers to what seem to be elusive questions.

Black Hole Thermodynamics

A CENTRAL PLAYER in these developments is the black hole. Black holes are a consequence of general relativity, Albert Einstein's 1915 geometric theory of gravitation. In this theory, gravitation arises from the curvature of spacetime, which makes objects move as if they were pulled by a force. Conversely, the curvature is caused by the presence of matter and energy. According to Einstein's equations, a sufficiently dense concentration of matter or energy will curve spacetime so extremely that it rends, forming a black hole. The laws of relativity forbid anything that went into a black hole from coming out again, at least within the classical (nonquantum) description of the physics. The point of no return, called the event horizon of the black hole, is of crucial importance. In the simplest case, the horizon is a sphere, whose surface area is larger for more massive black holes.

It is impossible to determine what is inside a black hole. No detailed information can emerge across the horizon and escape into the outside world. In disappearing forever into a black hole, however, a piece of matter does leave some traces. Its energy (we count any mass as energy in accordance with Einstein's $E = mc^2$) is permanently reflected in an increment in the black hole's mass. If the matter is captured while circling the hole, its associated angular momentum is added to the black hole's angular momentum. Both the mass and angular momentum of a black hole are measurable from their effects on spacetime around the hole. In this way, the laws of conservation of energy and angular momentum are upheld by black holes. Another fundamental law, the second law of thermodynamics, appears to be violated.

The second law of thermodynamics summarizes the familiar observation that most processes in nature are irreversible: a teacup falls from the table and shatters, but no one has ever seen shards jump up of their own accord and assemble into a teacup. The second law of thermodynamics forbids such inverse processes. It states that the entropy of an isolated physical system can never decrease; at best, entropy remains constant, and usually it increases. This law is central to physical chemistry and engineering; it is arguably the physical law with the greatest impact outside physics.

As first emphasized by Wheeler, when matter disappears into a black hole, its entropy is gone for good, and the second law seems to be transcended, made irrelevant. A clue to resolving this puzzle came in 1970, when Demetrious Christodoulou, then a graduate student of Wheeler's at Princeton, and Stephen W. Hawking of the University of Cambridge independently proved that in various processes, such as black hole mergers, the total area of the event horizons never decreases. The analogy with the tendency of entropy to increase led me to propose in 1972 that a black hole has entropy proportional to

THE AUTHOR

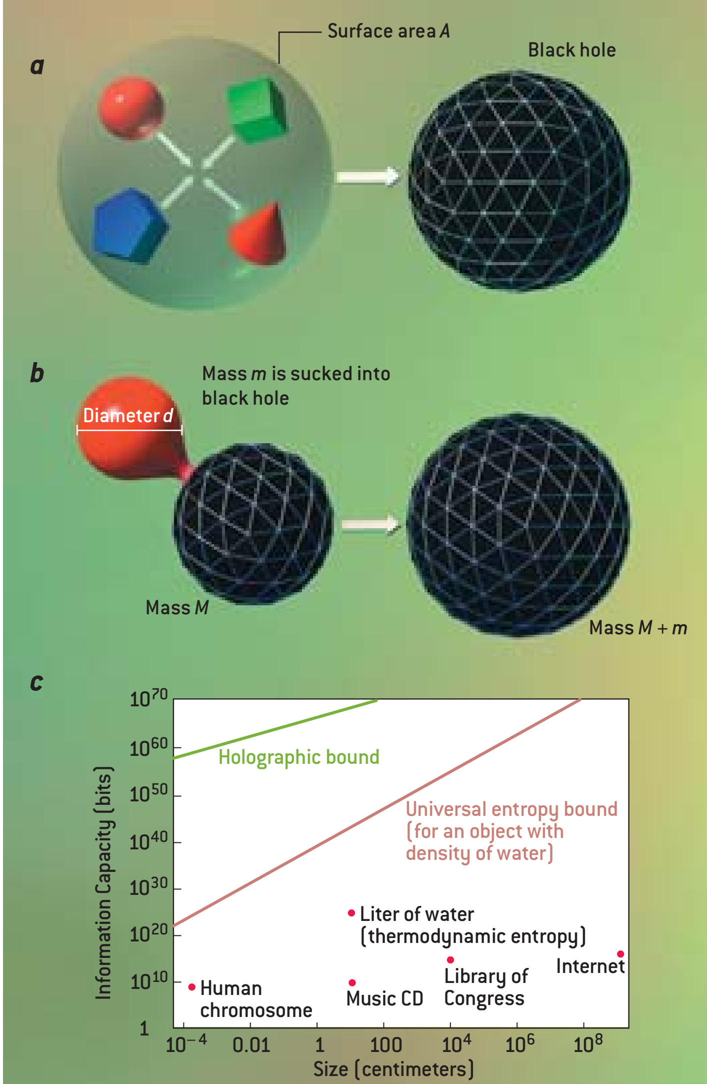
JACOB D. BEKENSTEIN has contributed to the foundation of black hole thermodynamics and to other aspects of the connections between information and gravitation. He is Polak Professor of Theoretical Physics at the Hebrew University of Jerusalem, a member of the Israel Academy of Sciences and Humanities, and a recipient of the Rothschild Prize. Bekenstein dedicates this article to John Archibald Wheeler (his Ph.D. supervisor 30 years ago). Wheeler belongs to the third generation of Ludwig Boltzmann's students: Wheeler's Ph.D. adviser, Karl Herzfeld, was a student of Boltzmann's student Friedrich Hasenöhrl.

the area of its horizon [*see illustration on preceding page*]. I conjectured that when matter falls into a black hole, the increase in black hole entropy always compensates or overcompensates for the "lost" entropy of the matter. More generally, the sum of black hole entropies and the ordinary entropy outside the black holes cannot decrease. This is the generalized second law—GSL for short.

The GSL has passed a large number of stringent, if purely theoretical, tests. When a star collapses to form a black hole, the black hole entropy greatly exceeds the star's entropy. In 1974 Hawking demonstrated that a black hole spontaneously emits thermal radiation, now known as Hawking radiation, by a quantum process [see "The Quantum Mechanics of Black Holes," by Stephen W. Hawking; SCIENTIFIC AMERICAN, January 1977]. The Christodoulou-Hawking theorem fails in the face of this phenomenon (the mass of the black hole, and therefore its horizon area, decreases), but the GSL copes with it: the entropy of the emergent radiation more than compensates for the decrement in black hole entropy, so the GSL is preserved. In 1986 Rafael D. Sorkin of Syracuse University exploited the horizon's role in barring information inside the black hole from influencing affairs outside to show that the GSL (or something very similar to it) must be valid for any conceivable process that black holes undergo. His deep argument makes it clear that the entropy entering the GSL is that calculated down to level X, whatever that level may be.

Hawking's radiation process allowed him to determine the proportionality constant between black hole entropy and horizon area: black hole entropy is precisely one quarter of the event horizon's area measured in Planck areas. (The Planck length, about 10^{-33} centimeter, is the fundamental length scale related to gravity and quantum mechanics. The Planck area is its square.) Even in thermodynamic terms, this is a vast quantity of entropy. The entropy of a black hole

LIMITS ON INFORMATION DENSITY



THE THERMODYNAMICS OF BLACK HOLES allows one to deduce limits on the density of entropy or information in various circumstances.

The holographic bound defines how much information can be contained in a specified region of space. It can be derived by considering a roughly spherical distribution of matter that is contained within a surface of area *A*. The matter is induced to collapse to form a black hole (*a*). The black hole's area must be smaller than *A*, so its entropy must be less than $A/4$ [*see illustration on preceding page*]. Because entropy cannot decrease, one infers that the original distribution of matter also must carry less than $A/4$ units of entropy or information. This result—that the maximum information content of a region of space is fixed by its area—defies the commonsense expectation that the capacity of a region should depend on its volume.

The universal entropy bound defines how much information can be carried by a mass *m* of diameter *d*. It is derived by imagining that a capsule of matter is engulfed by a black hole not much wider than it (*b*). The increase in the black hole's size places a limit on how much entropy the capsule could have contained. This limit is tighter than the holographic bound, except when the capsule is almost as dense as a black hole (in which case the two bounds are equivalent).

The holographic and universal information bounds are far beyond the data storage capacities of any current technology, and they greatly exceed the density of information on chromosomes and the thermodynamic entropy of water (*c*). —*J.D.B.*

LAURIE GRACE (*graph*)

THE INFORMATION CONTENT of a pile of computer chips increases in proportion with the number of chips or, equivalently, the volume they occupy. That simple rule must break down for a large enough pile of chips because eventually the information would exceed the holographic bound, which depends on the surface area, not the volume. The "breakdown" occurs when the immense pile of chips collapses to form a black hole.

one centimeter in diameter would be about 10^{66} bits, roughly equal to the thermodynamic entropy of a cube of water 10 billion kilometers on a side.

The World as a Hologram

THE GSL ALLOWS US to set bounds on the information capacity of any isolated physical system, limits that refer to the information at all levels of structure down to level X. In 1980 I began studying the first such bound, called the universal entropy bound, which limits how much entropy can be carried by a specified mass of a specified size [*see box on opposite page*]. A related idea, the holographic bound, was devised in 1995 by Leonard Susskind of Stanford University. It limits how much entropy can be contained in matter and energy occupying a specified volume of space.

In his work on the holographic bound, Susskind considered any approximately spherical isolated mass that is not itself a black hole and that fits inside a closed surface of area A. If the mass can collapse to a black hole, that hole will end up with a horizon area smaller than A. The black hole entropy is therefore smaller than $A/4$. According to the GSL, the entropy of the system cannot decrease, so the mass's original entropy cannot have been bigger than $A/4$. It follows that the entropy of an isolated physical system with boundary area A is necessarily less than $A/4$. What if the mass does not spontaneously collapse? In 2000 I showed that a tiny black hole can be used to convert the system to a black hole not much different from the one in Susskind's argument. The bound is therefore independent of the constitution of the system or of the nature of level X. It just depends on the GSL.

We can now answer some of those elusive questions about the ultimate limits of information storage. A device measuring a centimeter across could in principle hold up to 10^{66} bits—a mind-boggling amount. The visible universe contains at least 10^{100} bits of entropy, which could in principle be packed inside a sphere a tenth of a light-year across. Estimating the entropy of the universe is a difficult problem, however, and much larger numbers, requiring a sphere almost as big as the universe itself, are entirely plausible.

But it is another aspect of the holographic bound that is truly astonishing. Namely, that the maximum possible entropy depends on the boundary area instead of the volume. Imagine that we are piling up computer memory chips in a big heap. The number of transistors—the total data storage capacity—increases with the volume of the heap. So, too, does the total thermodynamic entropy of all the chips. Remarkably, though, the theoretical ultimate information capacity of the space occupied by the heap increases only with the surface area. Because volume increases more rapidly than surface area, at some point the entropy of all the chips would exceed the holographic bound. It would seem that either the GSL or our commonsense ideas of entropy and information capacity must fail. In fact, what fails is the pile itself: it would collapse under its own gravity and form a black hole before that impasse was reached. Thereafter each additional memory chip would increase the mass and surface area of the black hole in a way that would continue to preserve the GSL.

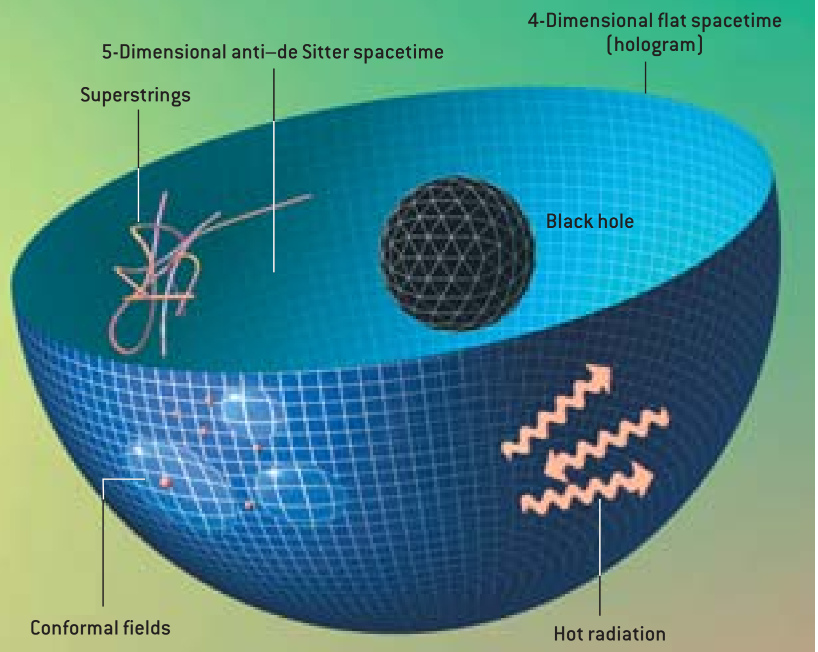
This surprising result—that information capacity depends on surface area—has a natural explanation if the holographic *principle* (proposed in 1993 by Nobelist Gerard 't Hooft of the University of Utrecht in the Netherlands and elaborated by Susskind) is true. In the everyday world, a hologram is a special kind of photograph that generates a full three-dimensional image when it is illuminated in the right manner. All the information describing the 3-D scene is encoded into the pattern of light and dark areas on the two-dimensional piece of film, ready to be regenerated. The holographic principle contends that an analogue of this visual magic applies to the full physical description of any system occupying a 3-D region: it proposes that another physical theory defined only on the 2-D boundary of the region completely describes the 3-D physics. If a 3-D system can be fully described by a physical theory operating solely on its 2-D boundary, one would expect the information content of the system not to exceed that of the description on the boundary.

A Universe Painted on Its Boundary

CAN WE APPLY the holographic principle to the universe at large? The real universe is a 4-D system: it has volume and extends in time. If the physics of our universe is holographic, there would be an alternative set of physical laws, operating on a 3-D boundary of spacetime

A HOLOGRAPHIC SPACETIME

TWO UNIVERSES of different dimension and obeying disparate physical laws are rendered completely equivalent by the holographic principle. Theorists have demonstrated this principle mathematically for a specific type of five-dimensional spacetime ("anti–de Sitter") and its four-dimensional boundary. In effect, the 5-D universe is recorded like a hologram on the 4-D surface at its periphery. Superstring theory rules in the 5-D spacetime, but a so-called conformal field theory of point particles operates on the 4-D hologram. A black hole in the 5-D spacetime is equivalent to hot radiation on the hologram—for example, the hole and the radiation have the same entropy even though the physical origin of the entropy is completely different for each case. Although these two descriptions of the universe seem utterly unalike, no experiment could distinguish between them, even in principle. *—J.D.B.*



somewhere, that would be equivalent to our known 4-D physics. We do not yet know of any such 3-D theory that works in that way. Indeed, what surface should we use as the boundary of the universe? One step toward realizing these ideas is to study models that are simpler than our real universe.

A class of concrete examples of the holographic principle at work involves so-called anti–de Sitter spacetimes. The original de Sitter spacetime is a model universe first obtained by Dutch astronomer Willem de Sitter in 1917 as a solution of Einstein's equations, including the repulsive force known as the cosmological constant. De Sitter's spacetime is empty, expands at an accelerating rate and is very highly symmetrical. In 1997 astronomers studying distant supernova explosions concluded that our universe now expands in an accelerated fashion and will probably become increasingly like a de Sitter spacetime in the future. Now, if the repulsion in Einstein's equations is changed to attraction, de Sitter's solution turns into the anti–de Sitter spacetime, which has equally as much symmetry. More important for the holographic concept, it possesses a boundary, which is located "at infinity" and is a lot like our everyday spacetime.

Using anti–de Sitter spacetime, theorists have devised a concrete example of the holographic principle at work: a universe described by superstring theory functioning in an anti–de Sitter spacetime is completely equivalent to a quantum field theory operating on the boundary of that spacetime [*see box above*]. Thus, the full majesty of superstring theory in an anti–de Sitter universe is painted on the boundary of the universe. Juan Maldacena, then at Harvard University, first conjectured such a relation in 1997 for the 5-D anti–de Sitter case, and it was later confirmed for many situations by Edward Witten of the Institute for Advanced Study in Princeton, N.J., and Steven S. Gubser, Igor R. Klebanov and Alexander M. Polyakov of Princeton University. Examples of this holographic correspondence are now known for spacetimes with a variety of dimensions.

This result means that two ostensibly very different theories—not even acting in spaces of the same dimension—are equivalent. Creatures living in one of these universes would be incapable of determining if they inhabited a 5-D universe described by string theory or a 4-D one described by a quantum field theory of point particles. (Of course, the structures of their brains might give them an overwhelming "commonsense" prejudice in favor of one description or another, in just the way that our brains construct an innate perception that our universe has three spatial dimensions; see the illustration on the opposite page.)

The holographic equivalence can allow a difficult calculation in the 4-D boundary spacetime, such as the behavior of quarks and gluons, to be traded for another, easier calculation in the highly symmetric, 5-D anti–de Sitter spacetime. The correspondence works the other way, too. Witten has shown that a black hole in anti–de Sitter spacetime corresponds to hot radiation in the alternative physics operating on the bounding spacetime. The entropy of the hole—a deeply mysterious concept—equals the radiation's entropy, which is quite mundane.

The Expanding Universe

HIGHLY SYMMETRIC and empty, the 5-D anti–de Sitter universe is hardly like our universe existing in 4-D, filled with matter and radiation, and riddled with violent events. Even if we approximate our real universe with one that has matter and radiation spread uniformly throughout, we get not an anti–de Sitter universe but rather a "Friedmann-Robertson-Walker" universe. Most cosmologists today concur that our universe resembles an FRW universe, one that is infinite, has no boundary and will go on expanding ad infinitum.

Does such a universe conform to the holographic principle or the holographic bound? Susskind's argument based on collapse to a black hole is of no help here. Indeed, the holographic bound deduced from black holes must break down in a uniform expanding universe. The entropy of a region uniformly filled with matter and radiation is truly proportional to its volume. A sufficiently large region will therefore violate the holographic bound.

In 1999 Raphael Bousso, then at Stanford, proposed a modified holographic bound, which has since been found to work even in situations where the bounds we discussed earlier cannot be applied. Bousso's formulation starts with any suitable 2-D surface; it may be closed like a sphere or open like a sheet of paper. One then imagines a brief burst of light issuing simultaneously and perpendicularly from all over one side of the surface. The only demand is that the imaginary light rays are converging to start with. Light emitted from the inner surface of a spherical shell, for instance, satisfies that requirement. One then considers the entropy of the matter and radiation that these imaginary rays traverse, up to the points where they start crossing. Bousso conjectured that this entropy cannot exceed the entropy represented by the initial surface—one quarter of its area, measured in Planck areas. This is a different way of tallying up the entropy than that used in the original holographic bound. Bousso's bound refers not to the entropy of a region at one time but rather to the sum of entropies of locales at a variety of times: those that are "illuminated" by the light burst from the surface.

Bousso's bound subsumes other entropy bounds while avoiding their limitations. Both the universal entropy bound and the 't Hooft-Susskind form of the holographic bound can be deduced from Bousso's for any isolated system that is not evolving rapidly and whose gravitational field is not strong. When these conditions are overstepped—as for a collapsing sphere of matter already inside a black hole—these bounds eventually fail, whereas Bousso's bound continues to hold. Bousso has also shown that his strategy can be used to locate the 2-D surfaces on which holograms of the world can be set up.

Augurs of a Revolution

RESEARCHERS HAVE proposed many other entropy bounds. The proliferation of variations on the holographic motif makes it clear that the subject has not yet reached the status of physical law. But although the holographic way of thinking is not yet fully understood, it seems to be here to stay. And with it comes a realization that the fundamental belief, prevalent for 50 years, that field theory is the ultimate language of physics must give way. Fields, such as the electromagnetic field, vary continuously from point to point, and they thereby describe an infinity of degrees of freedom. Superstring theory also embraces an infinite number of degrees of freedom. Holography restricts the number of degrees of freedom that can be present inside a bounding surface to a finite number; field theory with its infinity cannot be the final story. Furthermore, even if the infinity is tamed, the mysterious dependence of information on surface area must be somehow accommodated.

Holography may be a guide to a better theory. What is the fundamental theory like? The chain of reasoning involving holography suggests to some, notably Lee Smolin of the Perimeter Institute for Theoretical Physics in Waterloo, that such a final theory must be concerned not with fields, not even with spacetime, but rather with information exchange among physical processes. If so, the vision of information as the stuff the world is made of will have found a worthy embodiment. SA

OUR INNATE PERCEPTION that the world is three-dimensional could be an extraordinary illusion.

MORE TO EXPLORE

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DELPHIC ORACLE is shown inhaling vapors in this photographic interpretation, because new evidence supports ancient assertions that intoxicating gases were a source of her inspiration. In reality, the gases would have been invisible.

Questioning the Delphic Oracle

When science meets religion at this ancient Greek site, the two turn out to be on better terms than scholars had originally thought

The temple of Apollo, cradled in the spectacular mountainscape at Delphi, was the most important religious site of the ancient Greek world, for it housed the powerful oracle. Generals sought the oracle's advice on strategy. Colonists asked for guidance before they set sail for Italy, Spain and Africa. Private citizens inquired about health problems and investments. The oracle's advice figures prominently in the myths. When Orestes asked whether he should seek vengeance on his mother for murdering his father, the oracle encouraged him. Oedipus, warned by the oracle that he would murder his father and marry his mother, strove, with famous lack of success, to avoid his fate.

The oracle of Delphi functioned in a specific place, the *adyton*, or "no entry" area of the temple's core, and through a specific person, the Pythia, who was chosen to speak, as a possessed medium, for Apollo, the god of prophecy. Extraordinarily for misogynist Greece, the Pythia was a woman. And unlike most Greek priests and priestesses, the Pythia did not inherit her office through noble family connections. Although the Pythia had to be from Delphi, she could be old or young, rich or poor, well educated or illiterate. She went through a long and intense period of conditioning, supported by a sisterhood of Delphic women who tended the eternal sacred fire in the temple.

IMAGING BY TRUCOLLAGE

By John R. Hale, Jelle Zeilinga de Boer, Jeffrey P. Chanton and Henry A. Spiller

OPENING PHOTOGRAPH BY SANJAY KOTHARI

The Classical Explanation

TRADITION ATTRIBUTED the prophetic inspiration of the powerful oracle to geologic phenomena: a chasm in the earth, a vapor that rose from it, and a spring. Roughly a century ago scholars rejected this explanation when archaeologists digging at the site could find no chasm and detect no gases. The ancient testimony, however, is widespread, and it comes from a variety of sources: historians such as Pliny and Diodorus, philosophers such as Plato, the poets Aeschylus and Cicero, the geographer Strabo, the travel writer Pausanias, and even a priest of Apollo who served at Delphi, the famous essayist and biographer Plutarch.

Strabo (64 B.C.–A.D. 25) wrote: "They say that the seat of the oracle is a cavern hollowed deep down in the earth, with a rather narrow mouth, from which rises a *pneuma* [gas, vapor, breath; hence our words "pneumatic" and "pneumonia"] that produces divine possession. A tripod is set above this cleft, mounting which, the Pythia inhales the vapor and prophesies."

Plutarch (A.D. 46–120) left an extended eyewitness account of the workings of the oracle. He described the relationships among god, woman and gas by likening Apollo to a musician, the woman to his instrument and the *pneuma* to the plectrum with which he touched her to make her speak. But Plutarch emphasized that the *pneuma* was only a trigger. It was really the preconditioning and purification (certainly including sexual abstinence, possibly including fasting) of the chosen woman that made her capable of responding to exposure to the *pneuma*. An ordinary person could detect the smell of the gas without passing into an oracular trance.

Plutarch also recorded a number of physical characteristics about the *pneuma*. It smelled like sweet perfume. It was emitted "as if from a spring" in the *adyton* where the Pythia sat, but priests and consultants could on some occasions smell it in the antechamber where they waited for her responses. It could rise either as a free gas or in water. In Plutarch's day the emission had become weak and irregular, the cause, in his opinion, of the weakening influence of the Delphic oracle in world affairs. He suggested that either the vital essence had run out or that heavy rains had diluted it or a great earthquake more than four centuries earlier had partially blocked its vent. Maybe, he continued, the vapor had found a new outlet. Plutarch's theories about the lessening of the emission make it clear that he believed it originated in the rock below the temple.

A traveler in the next generation, Pausanias, echoes Plutarch's mention of the *pneuma* rising in water. Pausanias wrote that he saw on the slope above the temple a spring called Kassotis, which he had heard plunged underground and then emerged again in the *adyton,* where its waters made the women prophetic.

Plutarch and other sources indicate that during normal sessions the woman who served as Pythia was in a mild trance. She was able to sit upright on the tripod and might spend a considerable amount of time there (although when the line of consultants was long, a second and even a third Pythia might have

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ONLY SURVIVING DEPICTION of the priestess, or Pythia, at Delphi from the time the oracle was active reveals the low-ceilinged chamber and the Pythia seated on a tripod. In one hand she holds a sprig of laurel (Apollo's sacred tree); in the other, a cup, presumably containing water from a spring that bubbled up into the chamber, bringing with it gases that induced a trance. This mythological scene shows King Aegeus of Athens questioning the first Pythia, Themis. An Athenian potter made the cup in about 440 B.C.

Overview/*An Intoxicating Tale*

- For the past century, scholars have discounted as myth the traditional explanation that vapors rising out of the earth intoxicated, and inspired, the prophesying priestesses at Delphi.
- Recent scientific findings show that this description was, in fact, extraordinarily accurate.
- In particular, the authors have identified two geologic faults that intersect precisely under the site of the oracle.
- Furthermore, the petrochemical-rich layers in the limestone formations of the region most likely produced ethylene, a gas that induces a trancelike state and that could have risen through fissures created by the faults.

Extraordinarily for misogynist Greece, the Pythia was a woman. And she did not inherit her office through noble family connections.

to relieve her). She could hear the questions and gave intelligible answers. During the oracular sessions, the Pythia spoke in an altered voice and tended to chant her responses, indulging in wordplay and puns. Afterward, according to Plutarch, she was like a runner after a race or a dancer after an ecstatic dance.

On one occasion, which either Plutarch himself or one of his colleagues witnessed, temple authorities forced the Pythia to prophesy on an inauspicious day to please the members of an important embassy. She went down to the subterranean *adyton* unwillingly and at once was seized by a powerful and malignant spirit. In this state of possession, instead of speaking or chanting as she normally did, the Pythia groaned and shrieked, threw herself about violently and eventually rushed at the doors, where she collapsed. The frightened consultants and priests at first ran away, but they later came back and picked her up. She died after a few days.

The New Tradition

GENERATIONS OF SCHOLARS accepted these accounts. Then, in about 1900, a young English classicist named Adolphe Paul Oppé visited excavations being carried out by French archaeologists at Delphi. He failed to see any chasm or to hear reports of any gases, and he published an influential article in which he made three critical claims. First, no chasm or gaseous emission had ever existed in the temple at Delphi. Second, even if it had, no natural gas could produce a state resembling spiritual possession. Third, Plutarch's account of a Pythia who had a violent frenzy and died shortly afterward was inconsistent with the customary description of a Pythia sitting on the tripod and chanting her prophecies. Oppé concluded that all the ancient testimony could be explained away.

EXPERIMENTS with anesthesia conducted by Isabella Herb (*standing*) in the mid-20th century turned out to be crucial in solving the mystery of what gas might have been emitted beneath the temple at Delphi. Herb and her colleagues had discovered that low concentrations of ethylene could produce a trancelike state.

RUSH-PRESBYTERIAN-ST. LUKE'S MEDICAL CENTER

Oppé's debunking took the academic world by storm. His opinions were so strongly expressed that his theory became the new orthodoxy. The absence of the wide opening that the French archaeologists had expected seemed to prove his argument. Additional support for Oppé's theory came in 1950, when French archaeologist Pierre Amandry added the further negative that only a volcanic area, which Delphi was not, could have produced a gas such as the one described in the classical sources. The case seemed closed. The original tradition of the Greek and Latin authors lived on only in popular books and in the words of local guides, which, in Oppé's opinion, had been the source of the chasm and vapor myth in the first place.

The situation changed in the 1980s, when a United Nations Development Project undertook a survey in Greece of active faults (those along which earthquakes have been generated in the past few hundred years). As a member of that survey, one of us (de Boer, who is a geologist) noted exposed fault faces both east and west of the sanctuary. He interpreted them as marking the line of a fault that ran along the south slope of Mount Parnassus and under the site of the oracle. But being aware of the classical tradition and unaware of the modern skepticism and debunking, he attributed no special importance to his observation.

More than a decade later de Boer met another of us (Hale) at an archaeological site in Portugal where Hale, who is an archaeologist, sought de Boer's geological opinion on the evidence for earthquake damage at an ancient Roman villa. Over a bottle of wine, de Boer mentioned that he had seen the fault that ran under the temple at Delphi. Hale, who had learned the approved view as an undergraduate, contradicted him. But in the lively conversation that ensued, de Boer converted him with his description of the fault, his account of how faults could bring gases to the surface and his references to the classical authors. Realizing the importance of the observation for the interpretation of the ancient accounts, the two decided to form a team for further exploration of the site.

The Classical Explanation Revisited

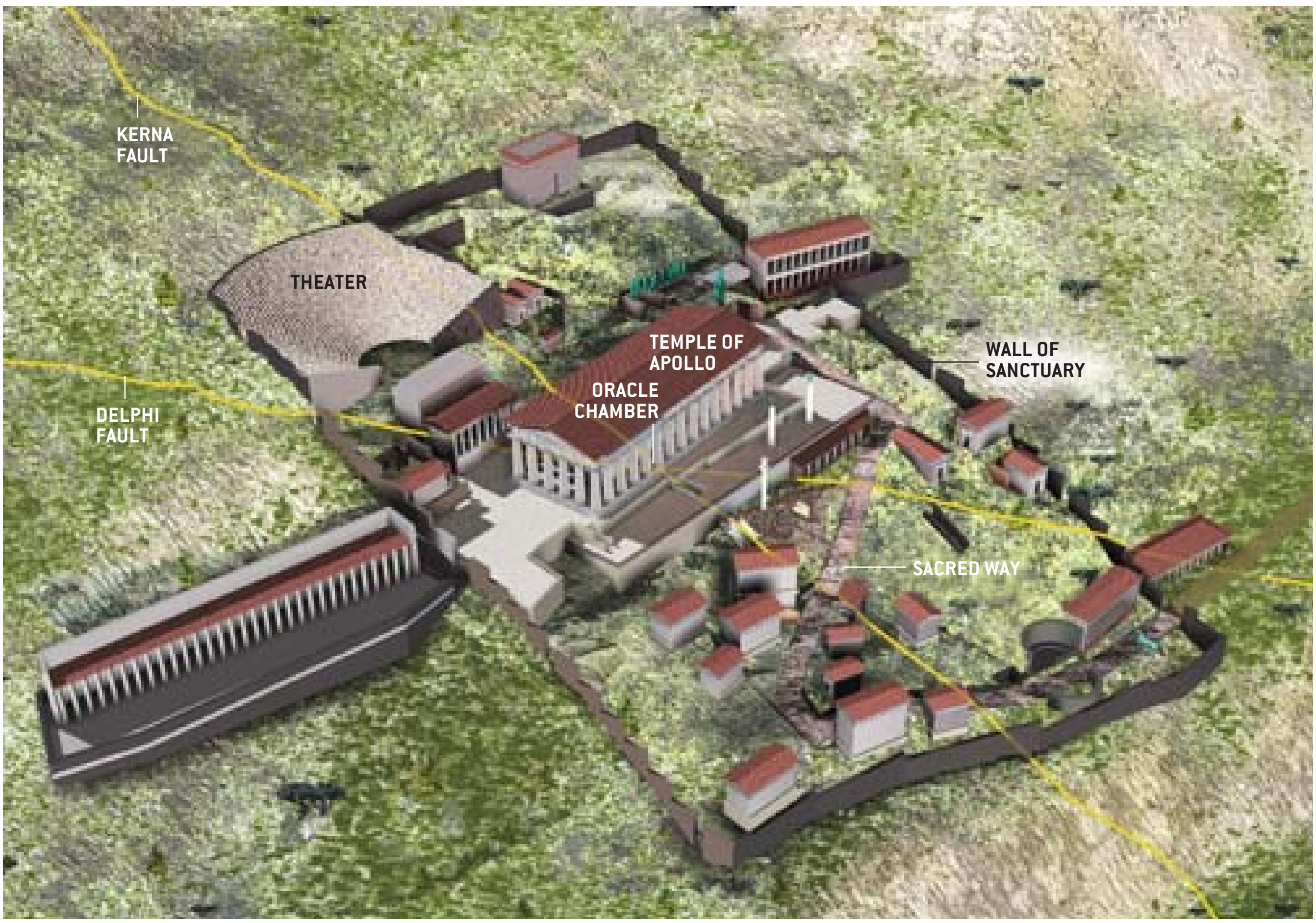
DURING OUR FIRST FIELD TRIP, in 1996, the two of us conducted geological surveys and examined the temple foundations that the French archaeologists had exposed. The temple has a number of anomalous features that would call for some special interpretation of its function even if the reports of Plutarch and others had not been preserved. First, the inner sanctum is sunken, lying two to four meters below the level of the surrounding floor. Second, it is asymmetrical: a break in the internal colonnade accommodates some now vanished structure or feature. Third, built directly into the foundations next to the recessed area is an elaborate drain for spring water, along with other subterranean passages. Thus, the temple of Apollo seemed designed to enclose a particular piece of terrain that included a water source, rather than to provide a house for the image of the god, the normal function of a temple building.

During that first exploration, we traced the major east-west fault line, called the Delphi fault, that de Boer had observed during the earlier survey. Later we were to discover the exposed face of a second fault in a ravine above the temple. This second line, which we named the Kerna fault, ran northwest-southeast and cut across the Delphi fault at the oracle site. A line of springs that ran through the sanctuary and intersected the temple marked the location of the Kerna fault below the ancient terracing and the accumulated debris from rockslides.

That same year a father-and-son archaeological and geological team, Michael D. Higgins and Reynold Higgins, published a book that suggested we were on the right track. In their *Geological Companion to Greece and the Aegean,* they noted that the line of springs did indeed suggest the presence of a "steep fault" running northwest-southeast through the sanctuary. They also pointed out that no geological reason necessitates rejecting the ancient tradition.

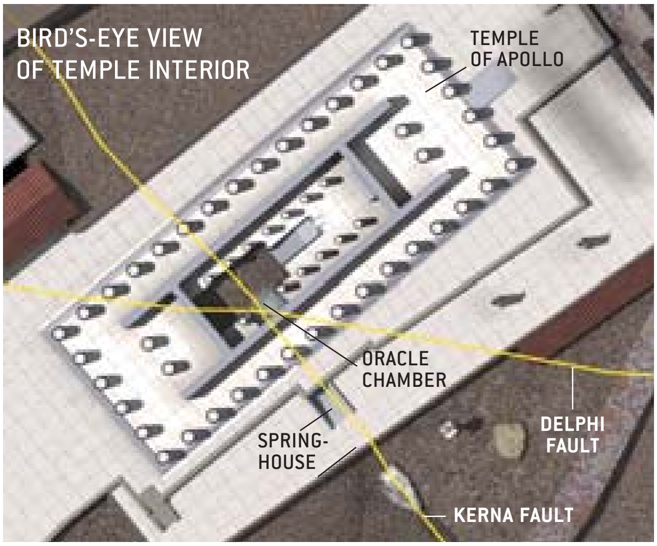
Higgins and Higgins theorized that the gas emitted might have been carbon dioxide. A decade earlier a different scientific team had detected such an emission at another temple of Apollo, the one at Hierapolis (modern Pamukkale) in Asia Minor (now Turkey, and home to the ruins of many great Greek cities). Following the lead of Strabo, modern researchers have discovered that the Apollo temple at Hierapolis had been deliberately sited over a vent of toxic gases, which in the finished temple emerged from a grotto in the building's foundations.

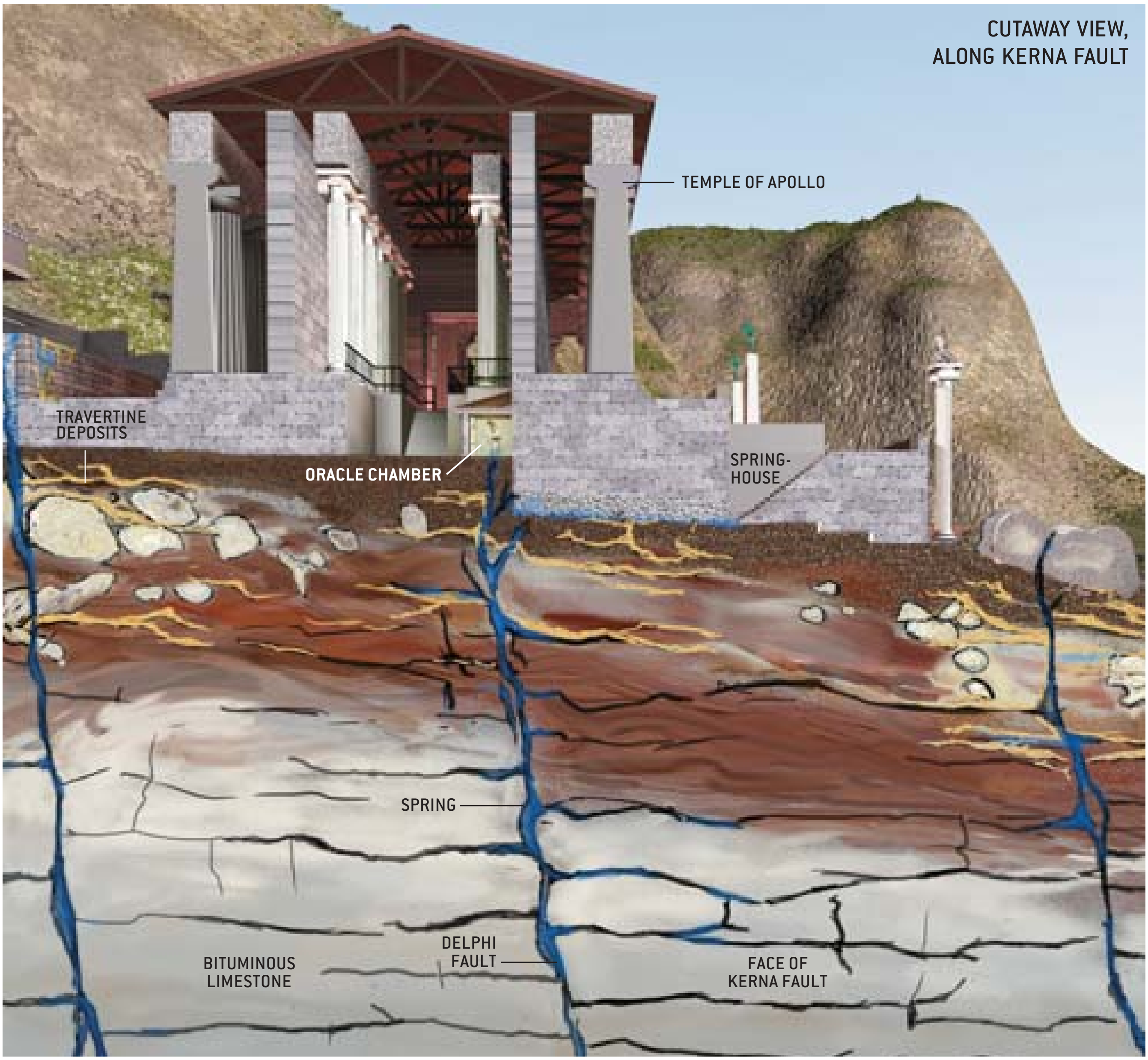
The temple at Hierapolis was not a place of prophecy, and the carbon dioxide was not so much intoxicating as toxic, claiming the lives of sacrificial animals, from sparrows to bulls.



DAVID FIERSTEIN

TWO GEOLOGIC FAULTS intersect under the Temple of Apollo at Delphi (*above* and *details on opposite page*). This intersection made the rock more permeable and provided pathways (*visible in cutaway*) along which both groundwater and gases were able to rise. Tectonic activity heated the limestone adjacent to the faults to temperatures high enough to vaporize some of its petrochemical constituents. These gaseous vapors then moved through the fissures created by the faults into the small, enclosed chamber lying below the floor level of the temple, where the oracle sat to prophesy.





DAVID FIERSTEIN; NINA FINKEL (*map*)

TEMPLE OF APOLLO is viewed (*at left*) along the line of the Delphi fault. The location of the oracle was near the block set inside the sunken area within the temple's foundations. In the photograph above, one of the authors (de Boer) sits on the block, in much the same spot where the Pythia would have sat on her tripod centuries ago.

SHANE SOLOW (*left*); JOHN HALE (*right*)

Even today the gas, which is emitted irregularly, kills sparrows that perch on the wire fence intended to keep people out. Other temples of Apollo in Turkey, however, *were* oracular, and they were built over active springs, such as those at Didyma and Claros. A link clearly seemed to be emerging between temples of Apollo and sites of geologic activity.

The Perfect Gas

ALTHOUGH THE NEWLY DISCOVERED faults at Delphi indicated that gases and spring water could have reached the surface through cracks that the faults created in the ground below the temple, they did not explain the generation of the gases themselves. De Boer, however, had observed travertine deposits, flows of calcite laid down by spring water, coating the slopes above the temple and even an ancient retaining wall. These flows suggested to him that the water had risen through deep layers of limestone to the surface, where it had deposited calcite mineralizations (a phenomenon also seen at Hierapolis in Turkey). A search through Greek geologic studies of Mount Parnassus revealed that among the Cretaceous rock formations in the vicinity of the temple were layers of bituminous limestone that had a petrochemical content as high as 20 percent.

De Boer now began to see a system taking shape. Faults, which were well exposed on the uplifted slopes of Mount Parnassus, had cut through bituminous limestone. Movement along the faults created friction that heated the limestone to a point at which the petrochemicals vaporized. They then rose along the fault with the spring water, especially at points where the presence of cross-faulting made the rock more permeable. Over time, gas emissions would decrease as calcitic crusts clogged the spaces inside the fault, only to be restored with the next tectonic slip.

De Boer's reasoning seemed in accord with the findings of the early 20th-century French archaeologists, who had finally reached bedrock under the *adyton* a few years after the publication of Oppé's article. Beneath a stratum of brown clay, they encountered rock that was "fissured by the action of the waters." We believe that faulting and fracturing rather than water may have created these fissures, although groundwater may have widened them over time; in early attempts to reach bedrock, the French archaeologists noted that the holes kept filling up with water. We also believe that the visible chasm in the *adyton* may have been a gaping fissure that extended into the layer of clay above the faulted bedrock.

As careful geologic research and reasoning solved riddle af-

THE AUTHORS

JOHN HALE, JELLE DE BOER, JEFF CHANTON and *RICK SPILLER* have formed an interdisciplinary team to investigate the Delphic oracle. Hale, an archaeologist at the University of Louisville, has written two previous articles for *Scientific American.* De Boer is a professor of geology at Wesleyan University. Chanton, a chemist, teaches in the department of oceanography at Florida State University, and toxicologist Spiller is director of the Kentucky Regional Poison Center.

A link clearly seemed to be emerging between temples of Apollo and sites of geologic activity.

ter riddle, we were still left with the question of what gases might have emerged. De Boer learned that geologists working in the Gulf of Mexico had analyzed gases that bubbled up along submerged faults. They had found that active faults in this area of bituminous limestone were producing light hydrocarbon gases such as methane and ethane. Could the same have been true at Delphi?

To find out, we asked for permission to take samples of spring water from Delphi, along with samples of the travertine rock laid down by ancient springs. We hoped to discover in this porous rock traces of the gases that were brought to the surface in earlier times. At this point, Chanton, who is a chemist, joined the team. In the travertine samples collected by de Boer and Hale, he found methane and ethane, the latter a decomposition product of ethylene. Chanton then visited Greece to collect water samples from springs in and around the oracle site. Analysis of the water from the Kerna spring in the sanctuary itself revealed the presence of methane, ethane and ethylene. Because ethylene has a sweet odor, the presence of this gas seemed to lend support to Plutarch's description of a gas that smelled like expensive perfume.

To help interpret the possible effects of such gases on human subjects in a confined space, one like the *adyton,* Spiller, a toxicologist, became a member of the project. His work with "huffers"—teenage drug users who get high on the fumes from substances such as glue and paint thinner, most of which contain light hydrocarbon gases—had shown a number of parallels with the behavior reported for the trance state of the Pythia.

Spiller uncovered even more parallels in the reports of experiments on the anesthetic properties of ethylene carried out more than half a century ago by pioneering American anesthesiologist Isabella Herb. She had found that a 20 percent mixture of ethylene produced unconsciousness but that lower concentrations induced a trance state. In most cases, the trance was benign: the patient remained conscious, was able to sit up and to respond to questions, experienced out-of-body feelings and euphoria, and had amnesia after being taken off the gas. But occasionally Herb would see violent reactions, the patient uttering wild, incoherent cries and thrashing about. Had a patient vomited during such a frenzy and ingested some of the vomit into the lungs, pneumonia and death would inevitably have followed. Thus, according to Spiller's analysis, inhaling ethylene could account for all the various descriptions of the *pneuma* at Delphi—its sweet odor and its variable effects on human subjects, including even the potential for death.

An Unexpected Inspiration

TWO THOUSAND YEARS AGO Plutarch was interested in reconciling religion and science. As priest of Apollo, he had to respond to religious conservatives who objected to the notion that a god might use a fluctuating natural gas to perform a miracle. Why not enter the woman's body directly? Plutarch believed that the gods had to rely on the materials of this corrupt and transitory world to accomplish their works. God though he was, Apollo had to speak his prophecies through the voices of mortals, and he had to inspire them with stimuli that were part of the natural world. Plutarch's careful observations and reporting of data about the gaseous emissions at Delphi show that the ancients did not try to exclude scientific inquiry from religious understanding.

The primary lesson we took away from our Delphic oracle project is not the well-worn message that modern science can elucidate ancient curiosities. Perhaps more important is how much we have to gain if we approach problems with the same broad-minded and interdisciplinary attitude that the Greeks themselves displayed. SA

MORE TO EXPLORE

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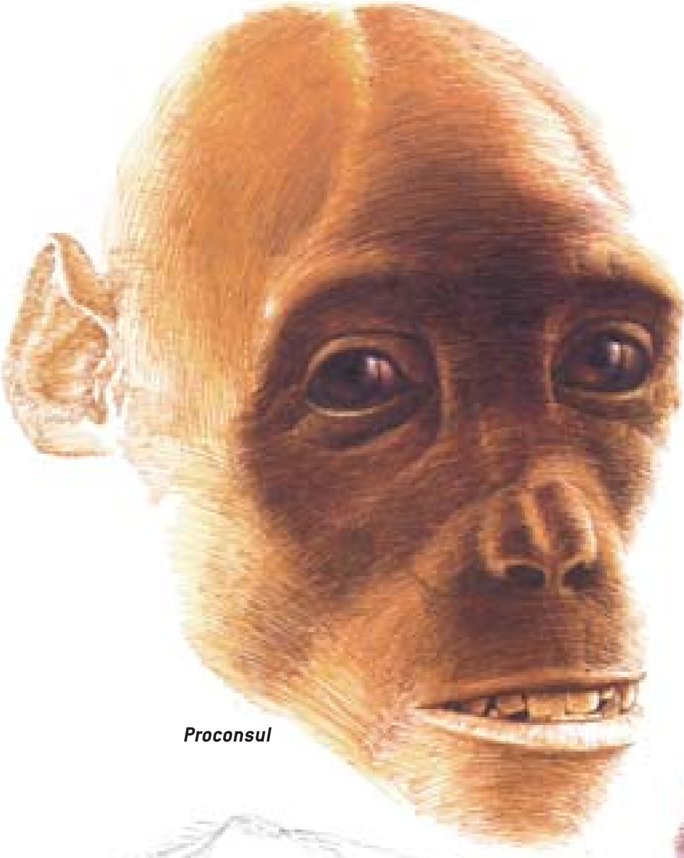


Proconsul

Dryopithecus

Sivapithecus

A DIVERSITY OF APES ranged across the Old World during the Miocene epoch, between 22 million and 5.5 million years ago. *Proconsul* lived in East Africa, *Oreopithecus* in Italy, *Sivapithecus* in South Asia, and *Ouranopithecus* and *Dryopithecus*—members of the lineage thought to have given rise to African apes and humans—in Greece and western and central Europe, respectively. These renderings were created through a process akin to that practiced by forensic illustrators. To learn more about how artist John Gurche drew flesh from stone, check out www.sciam.com/ontheweb

APES

During the Miocene epoch, as many as 100 species of apes roamed throughout the Old World. New fossils suggest that the ones that gave rise to living great apes and humans evolved not in Africa but Eurasia

By David R. Begun

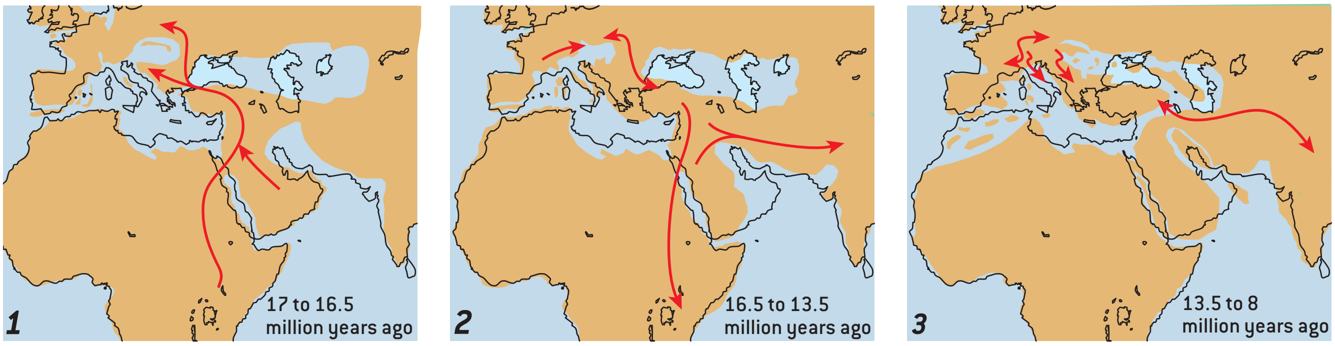
Fossil ape reconstructions by John Gurche

Ouranopithecus

Oreopithecus

"It is therefore probable that Africa was formerly inhabited by extinct apes closely allied to the gorilla and chimpanzee; as these two species are now man's closest allies, it is somewhat more probable that our early progenitors lived on the African continent than elsewhere."

So mused Charles Darwin in his 1871 work, *The Descent of Man.* Although no African fossil apes or humans were known at the time, remains recovered since then have largely confirmed his sage prediction about human origins. There is, however, considerably more complexity to the story than even Darwin could have imagined. Current fossil and genetic analyses indicate that the last common ancestor of humans and our closest living relative, the chimpanzee, surely arose in Africa, around six million to eight million years ago. But from where did this creature's own forebears come? Paleoanthropologists have long presumed that they, too,



had African roots. Mounting fossil evidence suggests that this received wisdom is flawed.

Today's apes are few in number and in kind. But between 22 million and 5.5 million years ago, a time known as the Miocene epoch, apes ruled the primate world. Up to 100 ape species ranged throughout the Old World, from France to China in Eurasia and from Kenya to Namibia in Africa. Out of this dazzling diversity, the comparatively limited number of apes and humans arose. Yet fossils of great apes—the large-bodied group represented today by chimpanzees, gorillas and orangutans (gibbons and siamangs make up the so-called lesser apes)—have turned up only in western and central Europe, Greece, Turkey, South Asia and China. It is thus becoming clear that, by Darwin's logic, Eurasia is more likely than Africa to have been the birthplace of the family that encompasses great apes and humans, the hominids. (The term "hominid" has traditionally been reserved for humans and protohumans, but scientists are increasingly placing our great ape kin in the definition as well and using another word, "hominin," to refer to the human subset. The word "hominoid" encompasses all apes—including gibbons and siamangs—and humans.)

Perhaps it should not come as a surprise that the apes that gave rise to hominids may have evolved in Eurasia instead of Africa: the combined effects of migration, climate change, tectonic activity and ecological shifts on a scale unsurpassed since the Miocene made this region a hotbed of hominoid evolutionary experimentation. The result was a panoply of apes, two lineages of which would eventually find themselves well positioned to colonize Southeast Asia and Africa and ultimately to spawn modern great apes and humans.

Paleoanthropology has come a long way since Georges Cuvier, the French natural historian and founder of vertebrate paleontology, wrote in 1812 that "*l'homme fossile n'existe pas*" ("fossil man does not exist"). He included all fossil primates in his declaration. Although that statement seems unreasonable today, evidence that primates lived alongside animals then known to be extinct—mastodons, giant ground sloths and primitive ungulates, or hoofed mammals, for example—was quite poor. Ironically, Cuvier himself described what scholars would later identify as the first fossil primate ever named, *Adapis parisiensis* Cuvier 1822, a lemur from the chalk mines of Paris that he mistook for an ungulate. It wasn't until 1837, shortly after Cuvier's death, that his disciple Édouard Lartet described the first fossil higher primate recognized as such. Now known as *Pliopithecus,* this jaw from southeastern France, and other specimens like it, finally convinced scholars that such creatures had once inhabited the primeval forests of Europe. Nearly 20 years later Lartet unveiled the first fossil great ape, *Dryopithecus,* from the French Pyrénées.

In the remaining years of the 19th century and well into the 20th, paleontologists recovered many more fragments of ape jaws and teeth, along with a few limb bones, in Spain, France, Germany, Austria, Slovakia, Hungary, Georgia and Turkey. By the 1920s, however, attention had shifted from Europe to South Asia (India and Pakistan) and Africa (mainly Kenya), as a result of spectacular finds in those regions, and the apes of Eurasia were all but forgotten. But fossil discoveries of the past two decades have rekindled intense interest in Eurasian fossil apes, in large part because paleontologists have at last recovered specimens complete enough to address what these animals looked like and how they are related to living apes and humans.

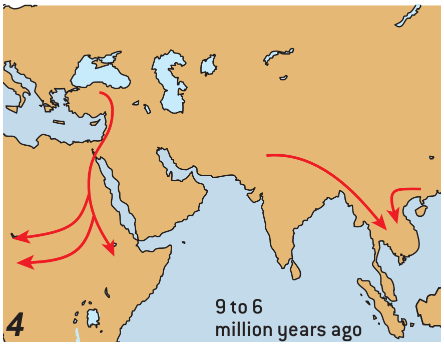
The First Apes

TO DATE, RESEARCHERS have identified as many as 40 genera of Miocene fossil apes from localities across the Old World—eight times the number that survive today. Such diversity seems to have characterized the ape family from the outset: almost as soon as apes appear in the fossil record, there are lots of them. So far 14 genera are known to have inhabited Africa during the early Miocene alone, between 22 million and 17 million years ago. And considering the extremely im-

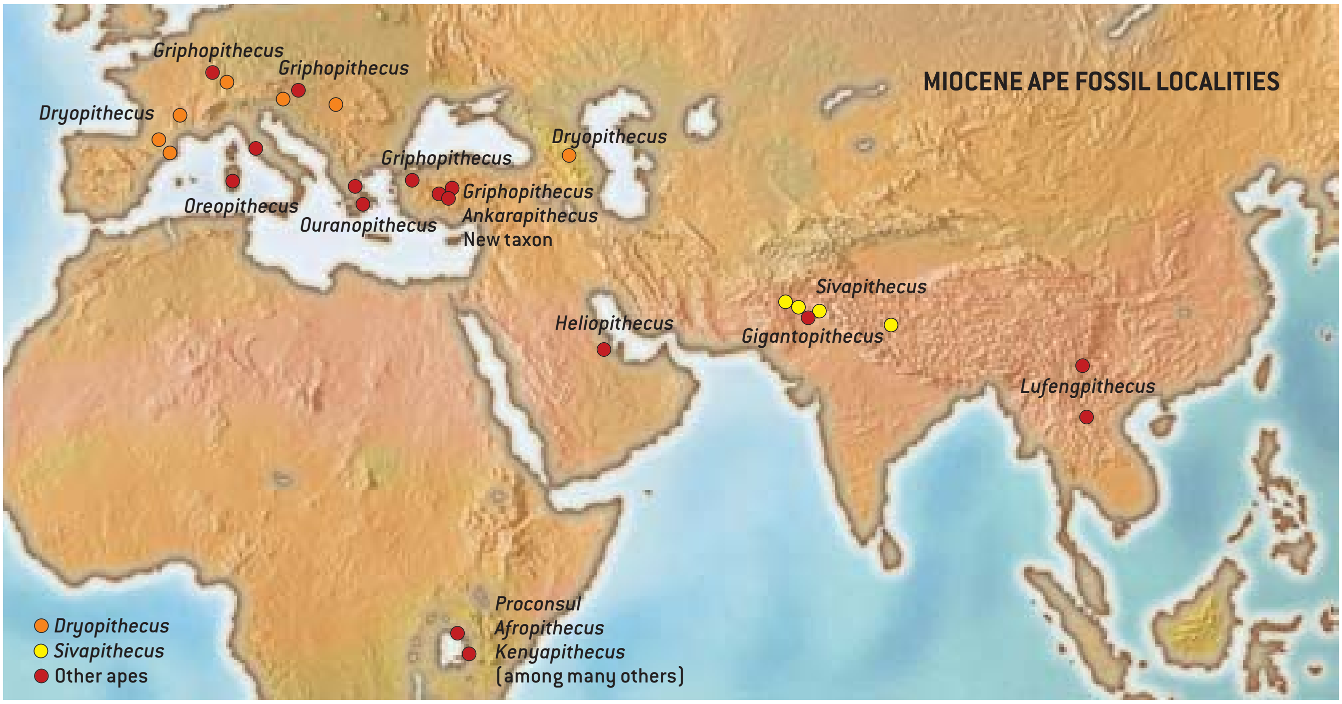
Overview/*Ape Revolution*

- Only five ape genera exist today, and they are restricted to a few pockets of Africa and Southeast Asia. Between 22 million and 5.5 million years ago, in contrast, dozens of ape genera lived throughout the Old World.
- Scientists have long assumed that the ancestors of modern African apes and humans evolved solely in Africa. But a growing body of evidence indicates that although Africa spawned the first apes, Eurasia was the birthplace of the great ape and human clade.
- The fossil record suggests that living great apes and humans are descended from two ancient Eurasian ape lineages: one represented by *Sivapithecus* from Asia (the probable forebear of the orangutan) and the other by *Dryopithecus* from Europe (the likely ancestor of African apes and humans).

LAURIE GRACE; MAP SOURCE: F. RÖGL IN *THE MIOCENE LAND MAMMALS OF EUROPE*, EDITED BY G. RÖSSNER AND K. HEISSIG. VERLAG DR. FRIEDRICH PFEIL, 1999



APES ON THE MOVE: Africa was the cradle of apekind, having spawned the first apes more than 20 million years ago. But it was not long before these animals colonized the rest of the Old World. Changes in sea level alternately connected Africa to and isolated it from Eurasia and thus played a critical role in ape evolution. A land bridge joining East Africa to Eurasia between 17 million and 16.5 million years ago enabled early Miocene apes to invade Eurasia (*1*). Over the next few million years, they spread to western Europe and the Far East, and great apes evolved; some primitive apes returned to Africa (*2*). Isolated from Africa by elevated sea levels, the early Eurasian great apes radiated into a number of forms (*3*). Drastic climate changes at the end of the Late Miocene wiped out most of the Eurasian great apes. The two lineages that survived—those represented by *Sivapithecus* and *Dryopithecus*—did so by moving into Southeast Asia and the African tropics (*4*).



perfect nature of the fossil record, chances are that this figure significantly underrepresents the number of apes that actually existed at that time.

Like living apes, these creatures varied considerably in size. The smallest weighed in at a mere three kilograms, hardly more than a small housecat; the largest tipped the scales at a gorillalike heft of 80 kilograms. They were even more diverse than their modern counterparts in terms of what they ate, with some specializing in leaves and others in fruits and nuts, although the majority subsisted on ripe fruits, as most apes do today. The biggest difference between those first apes and extant ones lay in their posture and means of getting around. Whereas modern apes exhibit a rich repertoire of locomotory modes—from the highly acrobatic brachiation employed by the arboreal gibbon to the gorilla's terrestrial knuckle walking—early Miocene apes were obliged to travel along tree branches on all fours.

To understand why the first apes were restricted in this way, consider the body plan of the early Miocene ape. The best-known ape from this period is *Proconsul,* exceptionally complete fossils of which have come from sites on Kenya's Rusinga Island [see "The Hunt for Proconsul," by Alan Walker and Mark Teaford; SCIENTIFIC AMERICAN, January 1989]. Specialists currently recognize four species of *Proconsul,* which ranged in size from about 10 kilograms to possibly as much as 80 kilograms. *Proconsul* gives us a good idea of the anatomy and locomotion of an early ape. Like all extant apes, this one lacked a tail. And it had more mobile hips, shoulders, wrists, ankles, hands and feet than those of monkeys, presaging the fundamental adaptations that today's apes and humans have for flexibility in these joints. In modern apes, this augmented mobility enables their unique pattern of movement, swinging from branch to branch. In humans, these capabilities have been exapted, or borrowed, in an evolutionary sense, for enhanced manipulation in the upper limb—something that allowed our ancestors to start making tools, among other things.

At the same time, however, *Proconsul*

THE AUTHOR

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What Is an Ape, Anyway?

MONKEY *PROCONSUL* GREAT APE

LIVING APES—chimpanzees, gorillas, orangutans, gibbons and siamangs—and humans share a constellation of traits that set them apart from other primates. To start, they lack an external tail, which is more important than it may sound because it means that the torso and limbs must meet certain requirements of movement formerly executed by the tail. Apes and humans thus have highly flexible limbs, enabling them to lift their arms above their heads and to suspend themselves by their arms. (This is why all apes have long and massive arms compared to their legs; humans, for their part, modified their limb proportions as they became bipedal.) For the same reason, all apes have broad chests, short lower backs, mobile hips and ankles, powerfully grasping feet and a more vertical posture than most other primates have. In addition, apes are relatively big, especially the great apes (chimps, gorillas and orangutans), which grow and reproduce much more slowly than other simians do. Great apes and humans also possess the largest brains in the primate realm and are more intelligent by nearly all measures—tool use, mirror self-recognition, social complexity and foraging strategy, among them—than any other mammal.

Fossil apes, then, are those primates that more closely resemble living apes than anything else. Not surprisingly, early forms have fewer of the defining ape characteristics than do later models. The early Miocene ape *Proconsul,* for example, was tailless, as evidenced by the morphology of its sacrum, the base of the backbone, to which a tail would attach if present. But *Proconsul* had not yet evolved the limb mobility or brain size associated with modern apes. Researchers generally agree that the 19-million-year-old *Proconsul* is the earliest unambiguous ape in the fossil record. The classification of a number of other early Miocene "apes"—including *Limnopithecus, Rangwapithecus, Micropithecus, Kalepithecus* and *Nyanzapithecus*—has proved trickier, owing to a lack of diagnostic postcranial remains. These creatures might instead be more primitive primates that lived before Old World monkeys and apes went their separate evolutionary ways. I consider them apes mainly because of the apelike traits in their jaws and teeth. *—D.R.B.*

and its cohorts retained a number of primitive, monkeylike characteristics in the backbone, pelvis and forelimbs, leaving them, like their monkey forebears, better suited to traveling along the tops of tree branches than hanging and swinging from limb to limb. (Intriguingly, one enigmatic early Miocene genus from Uganda, *Morotopithecus,* may have been more suspensory, but the evidence is inconclusive.) Only when early apes shed more of this evolutionary baggage could they begin to adopt the forms of locomotion favored by contemporary apes.

Passage to Eurasia

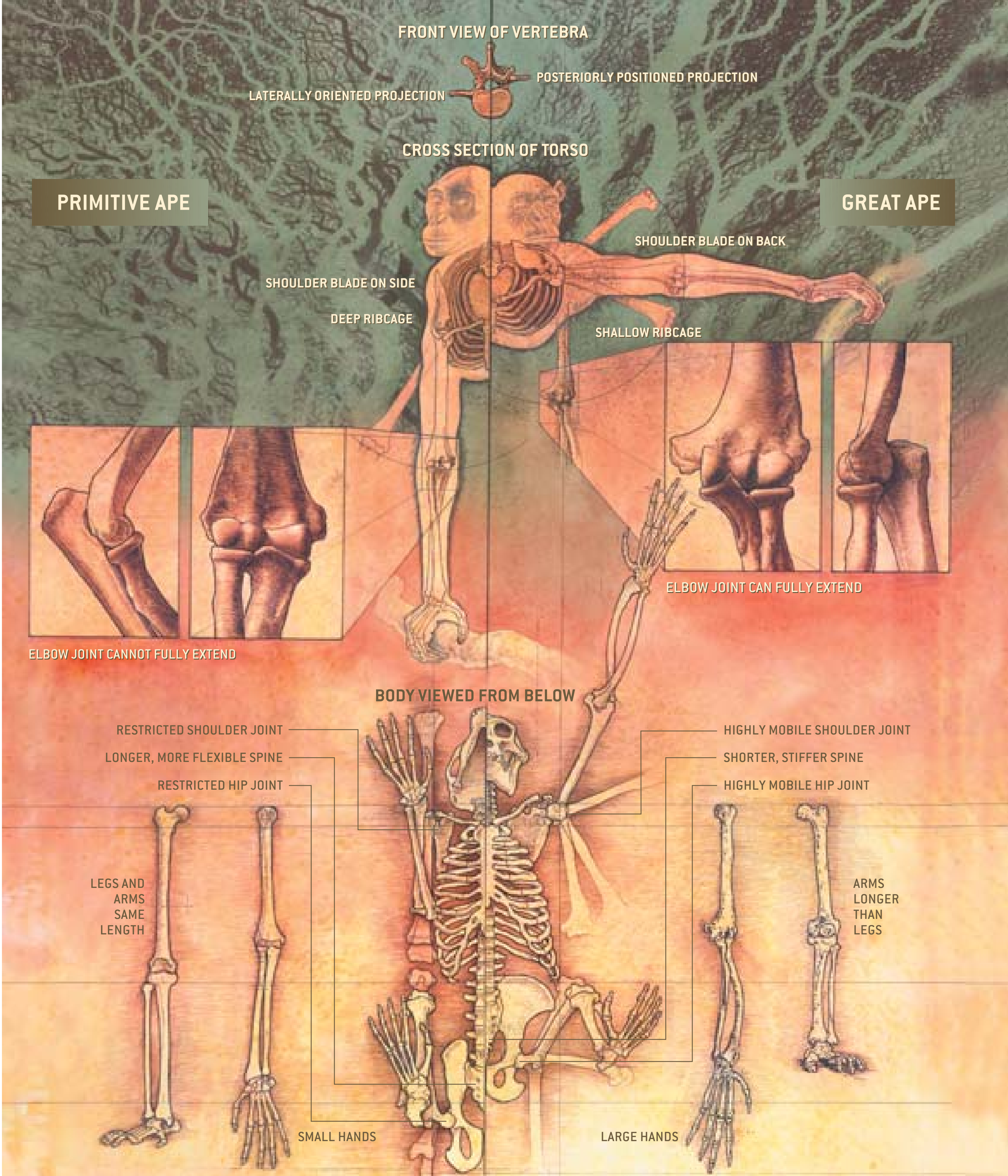
MOST OF THE EARLY Miocene apes went extinct. But one of them—perhaps *Afropithecus* from Kenya—was ancestral to the species that first made its way over to Eurasia some 16.5 million years ago. At around that time global sea levels dropped, exposing a land bridge between Africa and Eurasia. A mammalian exodus ensued. Among the creatures that migrated out of their African homeland were elephants, rodents, ungulates such as pigs and antelopes, a few exotic animals such as aardvarks, and primates.

The apes that journeyed to Eurasia from Africa appear to have passed through Saudi Arabia, where the remains of *Heliopithecus*, an ape similar to *Afropithecus,* have been found. Both *Afropithecus* and *Heliopithecus* (which some workers regard as members of the same genus) had a thick covering of enamel on their teeth—good for processing hard foods, such as nuts, and tough foods protected by durable husks. This dental innovation may have played a key role in helping their descendants establish a foothold in the forests of Eurasia by enabling them to exploit food resources not available to *Proconsul* and most earlier apes. By the time the seas rose to swallow the bridge linking Africa to Eurasia half a million years later, apes had ensconced themselves in this new land.

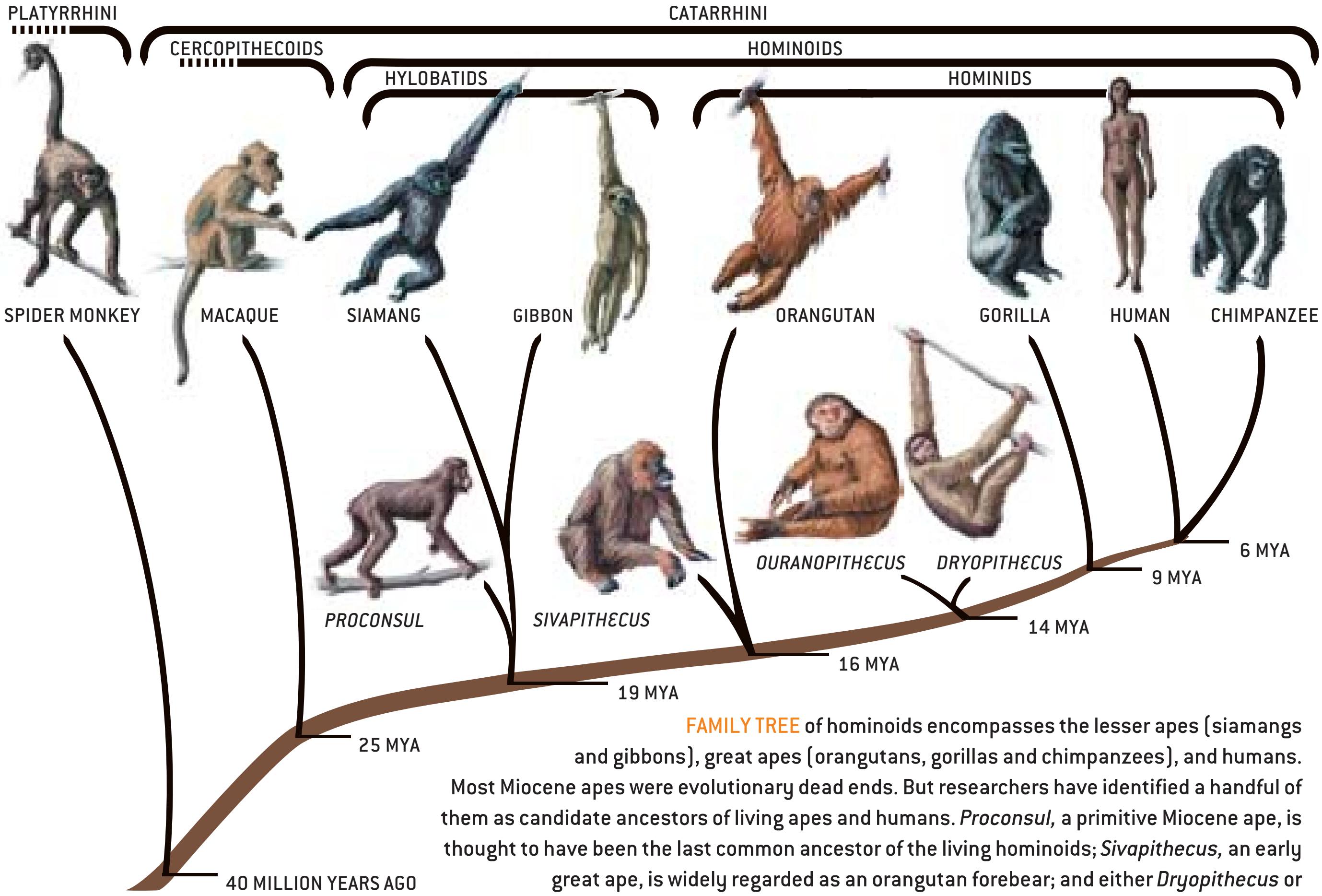
The movement of organisms into new environments drives speciation, and the arrival of apes in Eurasia was no exception. Indeed, within a geologic blink of an eye, these primates adapted to the novel ecological conditions and diversified into a plethora of forms—at least eight known in just 1.5 million years. This flurry of evolutionary activity laid the groundwork for the emergence of great apes and humans. But only recently have researchers begun to realize just how important Eurasia was in this regard. Paleontologists traditionally thought that apes more sophisticated in their food-processing abilities than *Afropithecus* and *Heliopithecus* reached Eurasia about 15 million years ago, around the time they first appear in Africa. This fit with the notion that they arose in Africa and then dispersed northward. New fossil evidence, however, indicates that advanced apes (those with massive jaws and large, grinding teeth) were actually in Eurasia far earlier than that. In 2001 and 2003 my colleagues and I described a more modern-looking ape, *Griphopithecus,* from 16.5-million-year-old sites in Germany and Turkey, pushing the Eurasian ape record back by more than a million years.

The apparent absence of such newer models in Africa between 17 million and 15 million years ago suggests that, contrary to the long-held view of this region as the wellspring of all ape forms, some hominoids began evolving modern cranial and dental features in Eurasia and returned to Africa changed into more advanced species only after the sea receded again. (A few genera—such as *Kenyapithecus* from Fort Ternan, Kenya—may have gone on to develop some postcranial adaptations to life on the ground, but for the most part, these animals still looked

PORTIA SLOAN (*this page*); JOHN GURCHE (*opposite page*)



GOING GREAT APE: Primitive ape body plan and great ape body plan are contrasted here. The earliest apes still had rather monkeylike bodies, built for traveling atop tree limbs on all fours. They possessed a long lower back; projections on their vertebrae oriented for flexibility; a deep rib cage; elbow joints designed for power and speed; shoulder and hip joints that kept the limbs mostly under the body; and arms and legs of similar length. Great apes, in contrast, are adapted to hanging and swinging from tree branches. Their vertebrae are fewer in number and bear a configuration of projections designed to stiffen the spine to support a more vertical posture. Great apes also have a broader, shallower rib cage; a flexible elbow joint that permits full extension of the arm for suspension; highly mobile shoulder and hip joints that allow a much wider range of limb motion; large, powerful, grasping hands; and upper limbs that are longer than their lower limbs.



FAMILY TREE of hominoids encompasses the lesser apes (siamangs and gibbons), great apes (orangutans, gorillas and chimpanzees), and humans. Most Miocene apes were evolutionary dead ends. But researchers have identified a handful of them as candidate ancestors of living apes and humans. *Proconsul,* a primitive Miocene ape, is thought to have been the last common ancestor of the living hominoids; *Sivapithecus,* an early great ape, is widely regarded as an orangutan forebear; and either *Dryopithecus* or *Ouranopithecus* may have given rise to African apes and humans.

like their early Miocene predecessors from the neck down.)

Rise of the Great Apes

BY THE END of the middle Miocene, roughly 13 million years ago, we have evidence for great apes in Eurasia, notably Lartet's fossil great ape, *Dryopithecus,* in Europe and *Sivapithecus* in Asia. Like living great apes, these animals had long, strongly built jaws that housed large incisors, bladelike (as opposed to tusklike) canines, and long molars and premolars with relatively simple chewing surfaces—a feeding apparatus well suited to a diet of soft, ripe fruits. They also possessed shortened snouts, reflecting the reduced importance of olfaction in favor of vision. Histological studies of the teeth of *Dryopithecus* and *Sivapithecus* suggest that these creatures grew fairly slowly, as living great apes do, and that they probably had life histories similar to those of the great apes—maturing at a leisurely rate, living long lives, bearing one large offspring at a time, and so forth. Other evidence hints that were they around today, these early great apes might have even matched wits with modern ones: fossil braincases of *Dryopithecus* indicate that it was as large-brained as a chimpanzee of comparable proportions. We lack direct clues to brain size in *Sivapithecus,* but given that life history correlates strongly with brain size, it is likely that this ape was similarly brainy.

Examinations of the limb skeletons of these two apes have revealed additional great ape–like characteristics. Most important, both *Dryopithecus* and *Sivapithecus* display adaptations to suspensory locomotion, especially in the elbow joint, which was fully extendable and stable throughout the full range of motion. Among primates, this morphology is unique to apes, and it figures prominently in their ability to hang and swing below branches. It also gives humans the ability to throw with great speed and accuracy. For its part, *Dryopithecus* exhibits numerous other adaptations to suspension, both in the limb bones and in the hands and feet, which had powerful grasping capabilities. Together these features strongly suggest that *Dryopithecus* negotiated the forest canopy in much the way that living great apes do. Exactly how *Sivapithecus* got around is less clear. Some characteristics of this animal's limbs are indicative of suspension, whereas others imply that it had more quadrupedal habits. In all likelihood, *Sivapithecus* employed a mode of locomotion for which no modern analogue exists—the product of its own unique ecological circumstances.

The *Sivapithecus* lineage thrived in Asia, producing offshoots in Turkey, Pakistan, India, Nepal, China and Southeast Asia. Most phylogenetic analyses concur that it is from *Sivapithecus* that the living orangutan, *Pongo pygmaeus,* is descended. Today this ape, which dwells in the rain forests of Borneo and Sumatra, is the sole survivor of that successful group.

In the west the radiation of great apes was similarly grand. From the earliest species of *Dryopithecus, D. fontani,* the one found by Lartet, several other species emerged over about three million years. More specialized descendants of this lineage followed suit. Within two million

PORTIA SLOAN

Bigfoot Ballyhoo

A FEW INDIVIDUALS, including some serious researchers, have argued that the *Sivapithecus* lineage of great apes from which the orangutan arose has another living descendant. Details of the beast's anatomy vary from account to account, but it is consistently described as a large, hirsute, nonhuman primate that walks upright and has reportedly been spotted in locales across North America and Asia. Unfortunately, this creature has more names than evidence to support its existence (bigfoot, yeti, sasquatch, nyalmo, rimi, raksi-bombo, the abominable snowman—the list goes on).

Those who believe in bigfoot (on the basis of suspicious hairs, feces, footprints and fuzzy videotape) usually point to the fossil great ape *Gigantopithecus* as its direct ancestor. *Gigantopithecus* was probably two to three times as large as a gorilla and is known to have lived until about 300,000 years ago in China and Southeast Asia.

ALLEGED bigfoot footprint, photographed near Coos Bay, Ore., in 1976.

There is no reason that such a beast could not persist today. After all, we know from the subfossil record that gorilla-size lemurs lived on the island of Madagascar until they were driven to extinction by humans only 1,000 years ago. The problem is that whereas we have fossils of 20-million-year-old apes the size of very small cats, we do not have even a single bone of this putative half-ton, bipedal great ape living in, among other places, the continental U.S. Although every primatologist and primate paleontologist I know would love for bigfoot to be real, the complete absence of hard evidence for its existence makes that highly unlikely. *—D.R.B.*

years four new species of *Dryopithecus* would evolve and span the region from northwestern Spain to the Republic of Georgia. But where *Dryopithecus* belongs on the hominoid family tree has proved controversial. Some studies link *Dryopithecus* to Asian apes; others position it as the ancestor of all living great apes. My own phylogenetic analysis of these animals—the most comprehensive in terms of the number of morphological characteristics considered—indicates that *Dryopithecus* is most closely related to an ape known as *Ouranopithecus* from Greece and that one of these two European genera was the likely ancestor of African apes and humans.

A *Dryopithecus* skull from Rudabánya, Hungary, that my colleagues and I discovered in 1999 bolsters that argument. Nicknamed "Gabi" after its discoverer, Hungarian geologist Gabor Hernyák, it is the first specimen to preserve a key piece of anatomy: the connection between the face and the braincase. Gabi shows that the cranium of *Dryopithecus,* like that of African apes and early fossil humans, had a long and low braincase, a flatter nasal region and an enlarged lower face. Perhaps most significant, it reveals that also like African apes and early humans, *Dryopithecus* was klinorhynch, meaning that viewed in profile its face tilts downward. Orangutans, in contrast—as well as *Proconsul,* gibbons and siamangs—have faces that tilt upward, a condition known as airorhinchy. That fundamental aspect of *Dryopithecus*'s cranial architecture speaks strongly to a close evolutionary relationship between this animal and the African apes and humans lineage. Additional support for that link comes from the observation that the *Dryopithecus* skull resembles that of an infant or juvenile chimpanzee—a common feature of ancestral morphology. It follows, then, that the unique aspects of adult cranial form in chimpanzees, gorillas and fossil humans evolved as modifications to the ground plan represented by *Dryopithecus* and living African ape youngsters.

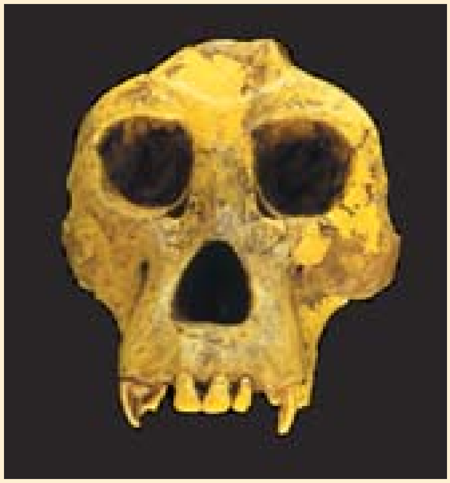
One more Miocene ape deserves special mention. The best-known Eurasian fossil ape, in terms of the percentage of the skeleton recovered, is seven-million-year-old *Oreopithecus* from Italy. First described in 1872 by renowned French paleontologist Paul Gervais, *Oreopithecus* was more specialized for dining on leaves than was any other Old World fossil monkey or ape. It survived very late into the Miocene in the dense and isolated forests of the islands of Tuscany, which would eventually be joined to one another and the rest of Europe by the retreat of the sea to form the backbone of the Italian peninsula. Large-bodied and small-brained, this creature is so unusual looking that it is not clear whether it is a primitive form that predates the divergence of gibbons and great apes or an early great ape or a close relative of *Dryopithecus*. Meike Köhler and Salvador Moyà-Solà of the Miquel Crusafont Institute of Paleontology in Barcelona have proposed that *Oreopithecus* walked bipedally along tree limbs and had a humanlike hand capable of a precision grip. Most paleoanthropologists, however, believe that it was instead a highly suspensory animal. Whatever *Oreopithecus* turns out to be, it is a striking reminder of how very diverse and successful at adapting to new surroundings the Eurasian apes were.

So what happened to the myriad species that did not evolve into the living great apes and humans, and why did the ancestors of extant species persevere? Clues have come from paleoclimatological studies. Throughout the middle Miocene, the great apes flourished in Eurasia, thanks to its then lush subtropical forest cover and consistently warm temperatures. These conditions assured a nearly continuous supply of ripe fruits and an

BETTMANN/CORBIS

Lucky Strikes

FOSSIL FINDS often result from a combination of dumb luck and informed guessing. Such was the case with the discoveries of two of the most complete fossil great ape specimens on record. The first of these occurred at a site known as Can Llobateres in the Vallès Penedès region of Spain. Can Llobateres had been yielding fragments of jaws and teeth since the 1940s, and in the late 1980s I was invited by local researchers to renew excavations there. The first year I discovered little other than how much sunburn and gazpacho I could stand. Undaunted, I returned for a second season, accompanied by my then seven-year-old son, André. During a planning session the day before the work was to begin, André made it clear that, after enduring many hours in a stifling building without air-conditioning, he had had enough, so I took him to see the site. We went to the spots my team had excavated the year before and then wandered up the hillside to other exposures that had looked intriguing but that we had decided not to investigate at that time. After poking around up there with André over the course of our impromptu visit, I resolved to convince my collaborators to dig a test pit in that area at some point during the season.



STELLAR SPECIMENS of *Dryopithecus,* one of the earliest great apes, have come from sites in Spain (*left*) and Hungary (*right*).

The next day we returned to the spot so that I could show a colleague the sediments of interest, and as we worked to clear off some of the overlying dirt, a great ape premolar popped out. We watched in amazement as the tooth rolled down the hill, seemingly in slow motion, and landed at our feet. A few days later we had recovered the first nearly whole face of *Dryopithecus* (*top*) and the most complete great ape from Can Llobateres in the 50-year history of excavations at the site. We subsequently traced the same sedimentological layer across the site and found some limb fragments in another area, which, when excavated more completely in the following year, produced the most complete skeleton of *Dryopithecus* known to this day.

Nine years later in Hungary my Hungarian colleagues and I were starting a new field season at a locality called Rudabánya. Historically, Rudabánya had yielded numerous *Dryopithecus* fossils, mostly teeth and skeletal remains. Intensive excavation over the previous two years, however, failed to turn up any material. For the 1999 season I thought we should concentrate our efforts on

easily traversed arboreal habitat with several tree stories. Climate changes in the late Miocene brought an end to this easy living. The combined effects of Alpine, Himalayan and East African mountain building, shifting ocean currents, and the early stages of polar ice cap formation precipitated the birth of the modern Asian monsoon cycle, the desiccation of East Africa and the development of a temperate climate in Europe. Most of the Eurasian great apes went extinct as a result of this environmental overhaul. The two lineages that did persevere—those represented by *Sivapithecus* and *Dryopithecus*—did so by moving south of the Tropic of Cancer, into Southeast Asia from China and into the African tropics from Europe, both groups tracking the ecological settings to which they had adapted in Eurasia.

The biogeographical model outlined above provides an important perspective on a long-standing question in paleoanthropology concerning how and why humans came to walk on two legs. To address that issue, we need to know from what form of locomotion bipedalism evolved. Lacking unambiguous fossil evidence of the earliest biped and its ancestor, we cannot say with certainty what that ancestral condition was, but researchers generally fall into one of two theoretical camps: those who think two-legged walking arose from arboreal climbing and suspension and those who think it grew out of a terrestrial form of locomotion, perhaps knuckle walking.

Your Great, Great Grand Ape

THE EURASIAN FOREBEAR of African apes and humans moved south in response to a drying and cooling of its environs that led to the replacement of forests with woodlands and grasslands. I believe that adaptations to life on the ground—knuckle walking in particular—were critical in enabling this lineage to withstand that loss of arboreal habitat and make it to Africa. Once there, some apes returned to the forests, others settled into varied woodland environments, and one ape—the one from which humans descended—eventually invaded open territory by committing to life on the ground.

Flexibility in adaptation is the consistent message in ape and human evolution. Early Miocene apes left Africa because of a new adaptation in their jaws and teeth that allowed them to exploit a diversity of ecological settings. Eurasian great apes evolved an array of skeletal adaptations that permitted them to live in varied environments as well as large brains to grapple with complex social and ecological challenges. These modifications made it possible for a few of them to survive the dramatic climate changes that took place at the end of the Miocene and return to

DAVID R. BEGUN

a dark layer of sediments suggestive of a high organic content often associated with abundant fossils. That layer was visible in a north-south cross section of the site, becoming lighter and, I thought, less likely to have fossils, toward the north. I asked Hungarian geologist and longtime amateur excavator Gabor Hernyák to start on the north end and work his way south toward the presumed pay dirt. But within less than a minute, Gabor excitedly summoned me back to the spot where I had left him. There, in what appeared to be the fossil-poor sediment, he had uncovered a tiny piece of the upper jaw of *Dryopithecus*. By the time we finished extracting the fossil, we had the most complete cranium of *Dryopithecus* ever found and the first one with the face still attached to the braincase (*bottom*).

This skull from Rudabánya—dubbed "Gabi" after its discoverer—illustrates more clearly than any other specimen the close relation between *Dryopithecus* and the African apes. I will always remember the look on my friend and co-director László Kordos's face when I went back to the village. (I made the 15-minute car trip in five minutes at most.) He was in the middle of e-mailing someone and looked up, quite bored, asking, "What's new?" "Oh, nothing much," I replied. "We just found a *Dryopithecus* skull." —*D.R.B.*

Africa, around nine million years ago. Thus, the lineage that produced African apes and humans was preadapted to coping with the problems of a radically changing environment. It is therefore not surprising that one of these species eventually evolved very large brains and sophisticated forms of technology.

As an undergraduate more than 20 years ago, I began to look at fossil apes out of the conviction that to understand why humans evolved we have to know when, where, how and from what we arose. Scientists commonly look to living apes for anatomical and behavioral insights into the earliest humans. There is much to be gained from this approach. But living great apes have also evolved since their origins. The study of fossil great apes gives us both a unique view of the ancestors of living great apes and humans and a starting point for understanding the processes and circumstances that led to the emergence of this group. For example, having established the connection between European great apes and living African apes and humans, we can now reconstruct the last common ancestor of chimps and humans: it was a knuckle-walking, fruit-eating, forest-living chimplike primate that used tools, hunted animals, and lived in highly complex and dynamic social groups, as do living chimps and humans.

Tangled Branches

WE STILL HAVE MUCH to learn. Many fossil apes are represented only by jaws and teeth, leaving us with little or no idea about their posture and locomotion, brain size or body mass. Moreover, paleontologists have yet to recover any remains of ancient African great apes. Indeed, there is a substantial geographic and temporal gap in the fossil record between representatives of the early members of the African hominid lineage in Europe (*Dryopithecus* and *Ouranopithecus*) and the earliest African fossil hominids.

Moving up the family tree (or, more accurately, family bush), we find more confusion in that the earliest putative members of the human family are not obviously human. For instance, the recently discovered *Sahelanthropus tchadensis,* a six-million- to seven-million-year-old find from Chad, is humanlike in having small canine teeth and perhaps a more centrally located foramen magnum (the hole at the base of the skull through which the spinal cord exits), which could indicate that the animal was bipedal. Yet *Sahelanthropus* also exhibits a number of chimplike characteristics, including a small brain, projecting face, sloped forehead and large neck muscles. Another creature, *Orrorin tugenensis,* fossils of which come from a Kenyan site dating to six million years ago, exhibits a comparable mosaic of chimp and human traits, as does 5.8-million-year-old *Ardipithecus ramidus kadabba* from Ethiopia. Each of these taxa has been described by its discoverers as a human ancestor [see "An Ancestor to Call Our Own," by Kate Wong; SCIENTIFIC AMERICAN, January]. But in truth, we do not yet know enough about any of these creatures to say whether they are protohumans, African ape ancestors or dead-end apes. The earliest unambiguously human fossil, in my view, is 4.4-million-year-old *Ardipithecus ramidus ramidus,* also from Ethiopia.

The idea that the ancestors of great apes and humans evolved in Eurasia is controversial, but not because there is inadequate evidence to support it. Skepticism comes from the legacy of Darwin, whose prediction noted at the beginning of this article is commonly interpreted to mean that humans and African apes must have evolved solely in Africa. Doubts also come from fans of the aphorism "absence of evidence is not evidence of absence." To wit, just because we have not found fossil great apes in Africa does not mean that they are not there. This is true. But there are many fossil sites in Africa dated to between 14 million and seven million years ago—some of which have yielded abundant remains of forest-dwelling animals—and not one contains great ape fossils. Although it is possible that Eurasian great apes, which bear strong resemblances to living great apes, evolved in parallel with as yet undiscovered African ancestors, this seems unlikely.

It would be helpful if we had a more complete fossil record from which to piece together the evolutionary history of our extended family. Ongoing fieldwork promises to fill some of the gaps in our knowledge. But until then, we must hypothesize based on what we know. The view expressed here is testable, as required of all scientific hypotheses, through the discovery of more fossils in new places. SA

MORE TO EXPLORE

Function, Phylogeny and Fossils: Miocene Hominoid Evolution and Adaptations. Edited by David R. Begun, Carol V. Ward and Michael D. Rose. Plenum Press, 1997.

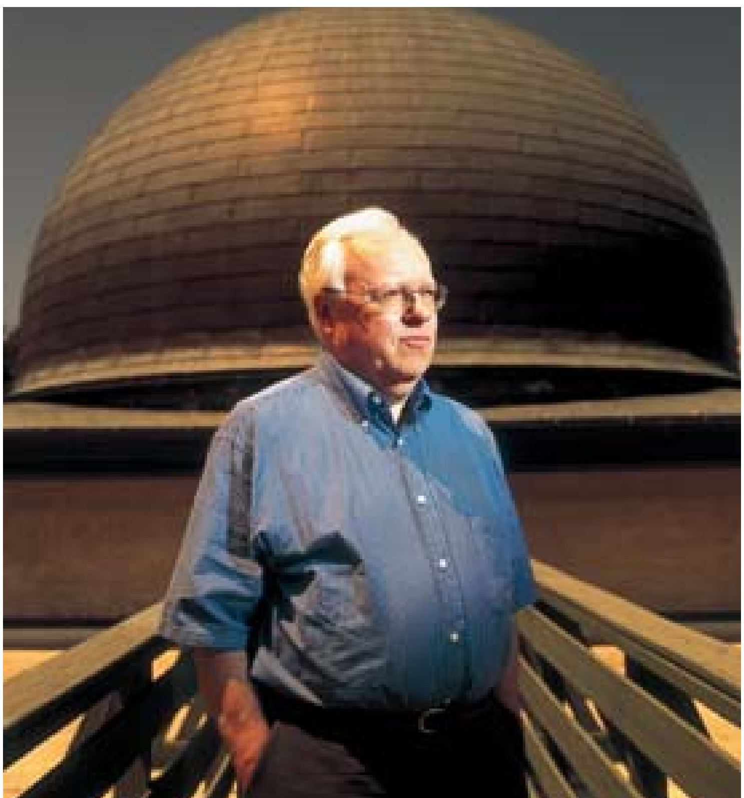
The Primate Fossil Record. Edited by Walter Carl Hartwig. Cambridge University Press, 2002.

Rudabánya: A Late Miocene Subtropical Swamp Deposit with Evidence of the Origin of the African Apes and Humans. László Kordos and David R. Begun in *Evolutionary Anthropology,* Vol. 11, Issue 1, pages 45–57; 2002.

Keeper of the Objects

With a shoestring budget, asteroid and comet watcher Brian Marsden looks out for Armageddon from the skies—and not without controversy By STEVE NADIS

Every day our neighborhood appears a bit more crowded—and dangerous. The band between Earth and Mars hosts swarms of swift-moving asteroids, some of which might eventually threaten our planet. The inner solar system is home to an estimated 1,000 to 1,500 asteroids a kilometer or greater in width, with perhaps a million rocks 50 meters and larger. Asteroid observations pour in at the rate of 15,000 or more a day.



JASON GROW

BRIAN MARSDEN: HEADS UP ON DANGER

- On national security: "There's a lot of concern about security these days, but does it go beyond terrorism and extend to outer space?"
- On the power of fear: "I think a good scare is occasionally helpful."
- Of 42 near-Earth asteroids with nonzero impact risk, only one object, 1997 XR2, warrants careful monitoring. See http://neo.jpl.nasa.gov/risk/

The burden of keeping track of near-Earth objects (NEOs)—asteroids and the occasional comets that pass through our vicinity—falls on Brian Marsden. Since 1978 he has directed the Minor Planet Center (MPC) at the Smithsonian Astrophysical Observatory in Cambridge, Mass. Sky watchers from all over the world send putative sightings to the MPC, which operates on behalf of the International Astronomical Union (IAU). The MPC processes and organizes data, identifies objects, computes orbits, assigns tentative names and disseminates information on a daily basis. For objects of special interest, the center solicits follow-up observations and requests archival data searches. "We are the focal point," Marsden says. "All the observations come here."

Marsden has served as the referee for all NEO sightings over the past 25 years—a period in which the total search effort has grown from a fledgling survey or two into a productive and efficient international network. At times this role has put him in the middle of controversy. Perhaps the most notorious incident occurred on March 11, 1998, when Marsden indicated on the MPC Web site that an asteroid discovered in December 1997 (then named 1997 XF11 and now called asteroid 35396) would make a close approach in 30 years. "The chance of an actual collision is small," he wrote, "but one is not entirely out of the question." That phrase set off a media circus that ranked among the 20 top science debacles of the century, according to *Discover* magazine.

Marsden admits that his word choice was "ill advised" but insists the calculation was correct at the time. He emphasized its uncertainty in the original notice and asked for more data. When the computations were redone a day later, incorporating orbital information from an old photograph, the threat vanished.

"Much as the incident was bad for my own reputation, we needed a scare like that to bring attention to this problem," Marsden remarks. "Many wondered whether I'd survive, but I'm still here." More important, he says, the field itself has prospered. In the wake of XF11 publicity, NASA increased funding for asteroid searches from $1 million to $3.5 million annually. In addition, groups at the University of Pisa in Italy and the Jet Propulsion Laboratory in Pasadena, Calif., began doing routine risk evaluations of potentially menacing objects. To date, the confirmed NEO total includes about 2,250 asteroids, a dozen comets that complete their orbits in less than 200 years, and 1,000 long-period comets (on orbits 200 years or longer) that pose no immediate concern.

It's a far cry from the early 1960s, when Marsden started adding to the list of some two dozen known NEOs with detections he made as a Yale University graduate student. After earning his Ph.D. in astronomy in 1965, he took a job at the Smithsonian, where he has worked ever since.

When Marsden began studying minor planets, "nobody cared about asteroids. They were dismissed as 'vermin of the sky.'" Now the study is a bona fide field, thanks to automated search programs such as the Lincoln Near-Earth Asteroid Research (LINEAR), run by the Massachusetts Institute of Technology Lincoln Laboratory, and NASA's Near-Earth Asteroid Tracking (NEAT), which collectively account for 90 percent of all NEO detections. The MPC is hard-pressed to keep up with the tide of incoming data, especially with a volume of main-belt asteroid observations 100 times as great as that for NEOs.

COLLISIONS with even small NEOs pose a threat: an object only 100 meters wide flattened these trees in Siberia in 1908.

Despite the workload, the MPC staff consists of only 2.5 people, including Marsden, who would like to keep the center running 24 hours a day. But that is not feasible: MPC gets just $130,000 a year from NASA, despite the agency's increased spending on NEO surveys. Other income, from subscriptions and donations, is not enough to cover the 80- to 100-hour workweeks. "Here we are saving the world, and they expect us to do it on our own time," Marsden quips.

More draining than the task at hand, however, is the time wasted on arguments. "There's a lot of infighting in this business. Not everybody likes everybody," he says. Besides the XF11 affair, which soured his relationships with several colleagues, Marsden has taken heat over access to information. He would rather not release data for tentative, single-night asteroid sightings—"one-night stands," as he calls them—both to ensure the data's reliability and to conform to the policies of leading programs such as LINEAR, NEAT and Spacewatch, which do not want unsubstantiated data made public. Astronomers who are anxious to see everything blame Marsden for impeding the information flow. "Brian follows the rules [set by the IAU], but the rules are flawed," Lowell Observatory astronomer Ted Bowell complains. He states that Marsden and others "often post orbital predictions without sharing the data that led to the calculations. I find that scientifically unacceptable."

Despite such criticism, the IAU recently extended the Smithsonian's contract for running the MPC through 2006. As for beyond that, rumors swirl about "hostile takeovers," in Marsden's words. Grant Stokes, who heads the LINEAR program, thinks that moving the MPC to a new home would be a mistake. "Brian and his center service the observing community wonderfully," Stokes says. "It's hard for me to believe this effort could be duplicated elsewhere."

Marsden tries to ignore the squabbles as he looks to the future. One day, inevitably, there will be a NEO on a collision course with Earth. With luck, it will be small and won't cause much damage. If it is spotted years or decades in advance, there might be time to intervene. "This is one threat we can do something about," he declares. Various defensive strategies have been proposed, including nudging an approaching asteroid with a nuclear blast or darkening part of the object's surface so that the thrust produced by radiated heat changes its orbit. Marsden is not sure how much money should be spent exploring these options but insists that "we have to do more than the dinosaurs."

Until now, the focus has been on large asteroids, a kilometer or bigger. The goal of the Spaceguard Survey, funded mainly by NASA, is to find 90 percent of these objects by 2008. More than 650 asteroids have been identified so far, perhaps half the total. (Astronomers estimate the total based on discovery rates from previous surveys.) Still, Marsden remarks, "we should begin planning the next step." Looking for 200- to 300-meter-wide objects is often proposed as a sensible target, but that would require new telescopes and roughly 10 times as much money.

Marsden turns 66 this month and would eventually like to hand the reins over to MPC's associate director, Gareth Williams, his partner since 1990. There's no timetable for a transition, says Williams, who admits he has "very big shoes to fill. Brian has been preeminent in the field since the 1960s." NASA Ames astronomer David Morrison, chair of the IAU's NEO working group, also lauds Marsden's efforts. Given Marsden's long tenure in the NEO field—starting out as he did when there was no "field" to speak of—Morrison is skeptical about talk of his impending retirement: "I think he'll do it forever." That is, of course, if the world doesn't end first. SA

Steve Nadis is a science writer based in Cambridge, Mass.

SOVFOTO

NIGHT VISION

Seeing Green

Humans cannot see in the dark, yet millions of television viewers regularly saw green, ghostlike tanks, soldiers and reporters negotiate the desert blackness during the recent Iraq war. Night vision tubes built into video cameras made it possible—the same technology that outdoor enthusiasts use to spot nocturnal animals or buoys on midnight waters and that police use to observe crooks in shrouded doorways.

No matter how dark the night, the stars, moon and man-made fixtures supply a small number of photons that such instruments can detect. The gear, which was invented during World War II by the military and has since trickled down to consumers, has advanced in "generations": rough standards of effectiveness defined by the U.S. Army Night Vision Labs at Fort Belvoir, Va. By the late 1980s, generations one and two gave way to the prevailing "Gen 3" products. Under a quarter moon (0.01 lux of light), they can distinguish a six-foot-tall person at 600 yards; quality monoculars cost $2,000 to $3,500.

The heart of any device is an intensifier tube that converts scarce photons into electrons and then amplifies and converts them into a visible image. The tubes do degrade—the best offer 10,000 hours of operation—but can be replaced. They are also limited, if not ineffective, in smoke, sandstorms and fog. For that reason, some soldiers use infrared goggles that capture the heat gradients of an enemy or vehicle—or the residual heat gradient left by one that recently passed by—and render a black-and-white image. The image sharpness is far less clear than night vision tubes, and if objects in a scene are at a uniform temperature—such as a pothole and a road—nothing appears. But infrared instruments can detect objects several miles away.

Manufacturers are thus beginning to produce prototypes of "fused" goggles that can overlay an infrared image onto a green intensifier-tube image. "I believe this will constitute the next generation of night vision," says Tom Peck, vice president of manufacturing engineering at ITT Industries Night Vision in Roanoke, Va., the U.S. military's dominant supplier. Then, although we will still live half our lives at night, we will never be in the dark. *—Mark Fischetti*

MONOCULAR LENS focuses the precious few photons available in darkness onto an intensifier tube, which is under vacuum. Inside, a photocathode (*1*) converts photons to electrons. A voltage accelerates the electrons to the microchannel plate (*2*), only a few thousandths of an inch (mils)—the thickness of two sheets of paper—away. The plate multiplies the electrons, and a second voltage accelerates them to the phosphor screen (*3*), again only a few mils away. It converts electrons back into photons that reach the eyepiece.

KENT SNODGRASS *Precision Graphics*

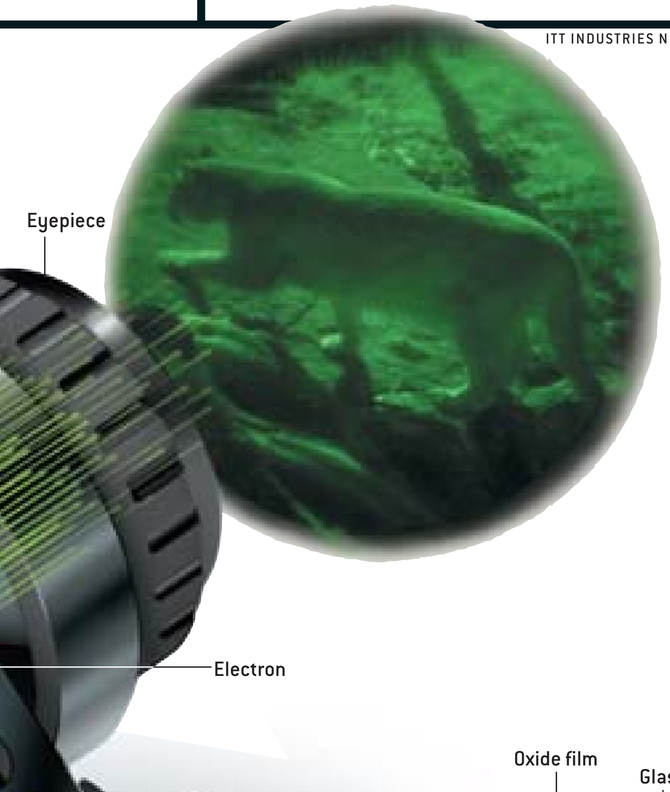
DID YOU KNOW . . .

➤ 6,000-VOLT CHALLENGE: The photocathode, microchannel plate and phosphor screen inside an intensifier tube nearly touch, yet the voltages that accelerate electrons across the tiny gaps between them range from 500 to 6,000 volts. "The greatest engineering challenge is keeping these parallel plates so close together yet so clean that we can apply such high voltages without any breakdown," says Tom Peck of ITT Industries Night Vision. Two AA batteries can provide the steep voltages at extremely low currents, using power-supply conversion circuitry, for 50 to 60 hours.

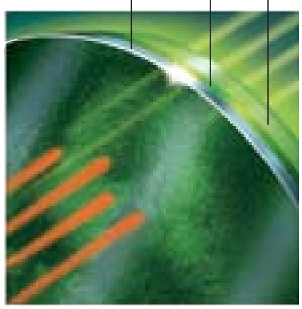
➤ MOUT CLOUT: Early generation-three instruments have trouble maintaining an image where lighting varies greatly, such as a city, reducing their effectiveness for soldiers engaged in so-called military operations in urban terrain (MOUT). By gating voltages and lowering currents inside the intensifier tube, manufacturers have increased the dynamic range of the devices. Now a soldier can spy a foe hiding in a dark shadow in a streetlit alley and keep a fix on him if the headlights of a passing car suddenly alter the scene.

➤ CAN'T SELL THIS: Night vision monoculars, binoculars, goggles, cameras, gun sights and other gear are "restricted for export" by the U.S. State Department. Any person or company selling or sending the technology abroad without licensing authorization could face severe fines and even time in prison.

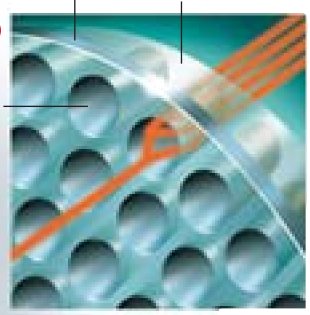
ITT INDUSTRIES NIGHT VISION



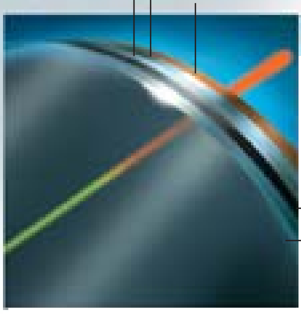
NIGHT VISION IMAGES are green because phosphors in the instruments emit light near the green wavelength of 550 nanometers, which is the "photopic maximum" for the human eye—the wavelength at which the eye is most sensitive, optimizing the brain's perception of contrast.



PHOSPHOR SCREEN emits a visible image as accelerated electrons strike, exciting phosphor particles, much like a cathode-ray tube. A film prevents photons from reflecting toward the photocathode, which would cause destructive feedback.



MICROCHANNEL PLATE has millions of tiny, slanted channels. Electrons enter and bounce off channel walls. Each collision produces two or three more electrons, multiplying the initial number many times. A film prevents positive ions created by some collisions from streaming back to the photocathode, which would degrade it. A voltage across the plate moves electrons through the microchannels.



PHOTOCATHODE'S LAYERS, only a few microns thick, are struck by photons. Their energy kicks out electrons. Gallium arsenide responds strongly to the predominantly red and near-infrared frequencies of light radiated by the night sky.

This month's topic was suggested by reader Chris Connor. Send your ideas to workingknowledge@sciam.com

Converging on the Couch

NEW DEVICES CONNECT THE STEREO AND TV TO THE HOME DATA NETWORK **BY W. WAYT GIBBS**

Convergence—the notion that computers, televisions, stereos and telephones would all become one—was the buzzword du jour a decade ago. Media and computer executives were quite taken with the "multimedia PCs" that had just come out, and many fancied that computers would soon be so capable that they would become the natural hub of communications and entertainment in the home. But the technology was actually not that capable, and the executives were soon distracted by a new fad called the Internet.

Now convergence is back, with grand pronouncements by Philips, Pioneer, Samsung and other big gadget makers promising that their forthcoming products will make our sofa-bound hours of entertainment that much more pleasurable. Communications, in this go-round, has been shoved to the backseat. The current thinking is that consumers will not add these novel devices, referred to as home media servers or digital media receivers, to their already cluttered entertainment centers because the gear is useful. They will buy the things because they are fun.

Fun is a hard quality to design, especially for computer engineers. Fun things just work; they do not frustrate. Designers of digital media toys face a double difficulty. First they must make the circuitry and software simple and reliable enough that couch potatoes can control them from a handheld remote while half-asleep. Then they must teach the machines to understand a babel of media formats, some of them encrypted with so-called digital-rights management codes. Viewers will be annoyed if restrictive copy prevention schemes thwart them from watching or listening to programs they have already paid for.

"POINT AND CLICK" takes on new meaning with remote-controlled digital media receivers.

JOHN FRASER

How well do the first entrants in the arena succeed in engineering the absence of annoyance? To find out, I spent several weeks with three network media appliances. Two of the devices are made by giants Sony and Hewlett-Packard. But the third is made by a young start-up named Prismiq, and as often happens, the entrepreneurs have been the most innovative.

The three gadgets are similar in several ways. Each runs \$200 to \$250, connects to your Ethernet network, and plugs into the TV and stereo—or just to the television if no stereo is handy. (Pricier models can be used with wireless WiFi networks as well.) Each moves digital media that you already own from your computers to your speakers and screens. So there is no monthly subscription fee, unlike TiVo. And each receiver comes with software that allows your computers to act as "servers," streaming photographs, music and other digital media to the receivers.

Sony, the master of miniaturization, squeezed its RoomLink Network Media Receiver into an elegant case the size of a hefty paperback. But the test gear from Sony arrived in three boxes weighing 20 kilograms. That is because the RoomLink works only with Sony's own Vaio line of PCs. If, like me, you do not already own a Vaio, the effective price of a RoomLink is not $200 but closer to $2,000.

Sony aims its Vaio computers at media creators, the sort who shoot their own digital movies and burn them to DVD. Such power users may appreciate the three feature-rich programs that one has to use on the PC to identify the MP3 files, photograph directories and video recordings that the RoomLink will offer in its menus. But each program has a dramatically different interface, and I found all the options confusing. It took about an hour of fiddling and reading the manuals to set up my playlists on the Vaio in the attic.

Three stories down in the family room, I grabbed the remote, turned on the RoomLink, selected the attic Vaio PC as the server (a curious and tiresome step when there is only one choice) and then started a photo slide show. This is where the fun began. Family snapshots are immeasurably more entertaining when viewed on television. Whether it is because they are brighter, larger and more vibrant than are prints in an album, or whether it is the weird sense of fame produced by seeing yourself and your loved ones on TV, I can't say. But it may be habit-forming.

After a week of use, however, little annoyances undermined the fun coolness of the RoomLink. The Vaio PC comes with a built-in video recorder. So while watching TV in the family room, a press of the "record" button saves the show to hard disk for later viewing. The RoomLink will also play movies copied directly to the Vaio from a personal video camera.

But it will not play video clips from other sources—downloaded from the Web, for example. The software refused to run any of the home movies I had made using our digital camera and (non-Sony) computer. In its zeal to discourage illegal copies of commercial films, Sony's video software cut me off from movies of my son eating his first solid food.

The HP Digital Media Receiver is as simple as the Sony is sophisticated. It does only two things—photos and music—but it does them well. The software installed quickly, asked which media folders to monitor, and then disappeared; I never

Slide shows with soundtracks are definitely addictive. But are they enough fun to justify the cost?

had to touch it again. Media files from both of my Windows PCs magically appeared in the menus without any irritating "select server" screens. (None of the three receivers were able to work with my third computer, which runs Linux, nor do they support Apple's Mac OS.)

The receiver automatically categorized the more than 600 MP3 music files on my machines by artist name, album title, even genre. And unlike the Sony, the HP gadget could play music in the background while displaying all the photos in a folder. Slide shows with soundtracks are definitely addictive. But are they enough fun to justify the $200 cost?

Personally, I expect $200 to buy more. A new version of the Prismiq MediaPlayer released in May, for example, plays music and photos simultaneously. But the MediaPlayer comes with a keyboard and has a simple built-in Web browser that I used to check e-mail, weather reports, movie times and restaurant reviews. The Prismiq can play Internet radio stations. I listened to one from Iran and another from Russia. The highly compressed radio music falls short of the CD quality of music files from my own computers, but it was thrilling to tune in music from halfway around the planet.

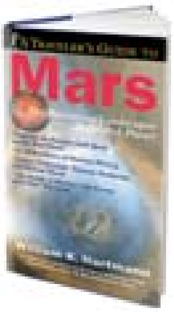
And the MediaPlayer can run videos—not merely the homemade variety but also movies downloaded from the Internet or even from DVDs. My wife and I watched the video of our son pushing his little spoon out of his mouth over and over, as Johnny Cash's song "Bonanza" played in the background.

But here the Prismiq device, too, gets tripped up by the recording industry's self-inflicted limitations. The MediaPlayer can display only unencrypted video files. Because DVD movie files are encrypted, that means using special software that cracks their codes and copies them to a hard disk. Such software appears to violate the Digital Millennium Copyright Act. And yet the software is readily available and, ahem, is compatible with the Prismiq receiver.

Wouldn't it be fun to download a movie rental—from a service such as MovieLink, for example—and watch it from the couch rather than the computer chair? I tried it; it doesn't work. By design, MovieLink stored the films I rented and downloaded in an encrypted file format that will not play on any of the media receivers. To watch *A River Runs Through It* on the television, I had to connect long cables from my computer to the stereo and TV, then fuss with Windows for half an hour to get the player software to show the movie on the correct screen. And so frustration trumps fun once again. SA

Better Red Than Dead

A VETERAN RESEARCHER MARSHALS EVIDENCE THAT MARS IS GEOLOGICALLY ALIVE **BY GEORGE MUSSER**



A TRAVELER'S GUIDE TO MARS: THE MYSTERIOUS LANDSCAPES OF THE RED PLANET
by William K. Hartmann
Workman Publishing, New York, 2003 ($18.95)

Is Mars letting us down? In the 1980s and early 1990s, many planetary scientists got the sinking feeling that the Red Planet wasn't living up to humanity's expectations. Its surface was lifeless, its volcanoes extinct. Evidence of an Earth-like past was looking shaky. When I entered graduate school in planetary science during this period, I was discouraged from doing research on Mars, as the data from the Viking spacecraft of the mid-1970s had been thoroughly picked over. Follow-up missions from the U.S. and the Soviet Union floundered. Scientists found themselves pitted against "Face on Mars" conspiracy theorists in television debates.

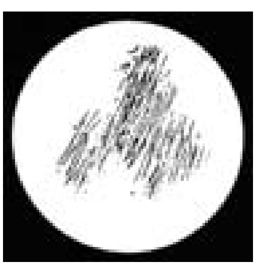
Even through these dark years, veteran researcher William K. Hartmann held that Mars was not, in fact, geologically dead. He reasoned that some of the terrain was so fresh, so free of meteor craters, that at least some of the volcanoes were not extinct, merely dormant. It was a minority view—but no longer. New space missions have found signs not just of recent volcanism but of glaciers, liquid water and periodic climate change. Things are looking up again for the Red Planet, and Hartmann's latest book encapsulates this understanding.

The author, who works at the Planetary Science Institute in Tucson, Ariz., has been around long enough to see sentiment about Mars go through several cycles of bust and boom. He recalls the first observations by the Mariner 9 spacecraft in 1971. Its predecessors had already dashed hopes of a world covered in vegetation, and the global dust storm that greeted Mariner 9's arrival deepened the gloom. But as the dust cleared, a mountain with no equal in human experience—so big that it would span the state of Missouri—slowly came into view: Olympus Mons. The outlines of a sublime canyon system gradually took shape: Valles Marineris. It was as if the dust had erased all those prior expectations and allowed Mars to reveal itself on its own terms.

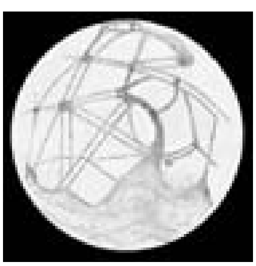
Hartmann's book is being marketed as a travel guide, but it is best thought of as an extended argument for the persistence of geologic activity. The main concession to the guidebook conceit is its region-by-region approach. Going (roughly) from the oldest terrain to the youngest, the book provides a close reading of the most scientifically and aesthetically compelling images. It shows how planetary geologists reconstruct Martian history by looking at the relationships among formations: whether a crater punctures a lava flow, say, or a sand dune covers a crater floor. The book includes a number of photographs of similar-looking formations on Earth, as well as interpretive paintings. (Hartmann is a well-known astronomical artist.)

Mixed in with this analysis are primers on geologic processes; the explanations of impact cratering and the stability of liquid water are models of elegance. The book hits pretty much every aspect of Martian surface science. (For the interior, atmosphere and natural satellites, you'll need to turn elsewhere.) A series of box-

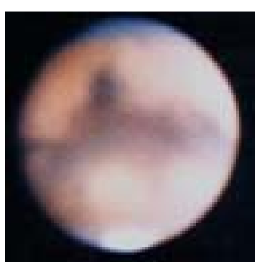
VIEWS OF MARS have progressed from visual sketches to detailed photographs. These images all show roughly the same area, Syrtis Major.



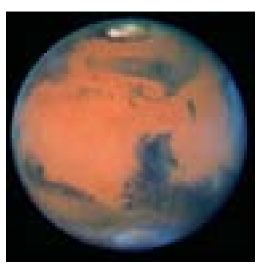
Christiaan Huygens, 1659



Giovanni Schiaparelli, 1888



Telescopic view, early 1960s



Hubble Space Telescope, 1997

Mars Global Surveyor, 2002

COURTESY OF WORKMAN PUBLISHING, INC.; NASA/JPL/MALIN SPACE SCIENCE SYSTEMS (*Mars Global Surveyor*) es give personal reminiscences and commentary on subjects such as the brain drain caused by the lack of jobs for young scientists, a situation with which my generation is all too familiar.

Although the book isn't technical, its narrative is probably too nonlinear for an absolute beginner. The structure is uneven. Some chapters are fleshed out step by step; others flit over important questions, as if topics are being force-fit into the region-by-region approach. The text occasionally falls into the same trap as writings by many other scientists and journalists—something I call the received-wisdom syndrome. In one example, chapter 25 states that because asteroids formed 4.5 billion years ago, almost all meteorites are 4.5 billion years old. How do scientists know that? To explain, the sentence should be flipped around: "Because almost all meteorites are 4.5 billion years old, asteroids must have formed that long ago."

A beginner may also have trouble interpreting the images. The captions make reference to shorelines, landing sites, mountain ranges, river bends, plateaus. But few images have labels or arrows to indicate exactly where these features are. The fold-out global maps are skimpy, but that is easily solved by reading the book alongside either the map in the February 2001 issue of *National Geographic* or the one put out by the U.S. Geological Survey (astrogeology.usgs.gov/Gallery/MapsAndGlobes).

Someone who already knows the basics about the Red Planet will read right past these hiccups, and the reward is an almost participatory experience, giving an intimacy with the planet and with the way a planetary scientist thinks. As Hartmann writes in the introduction, most recent Mars images "have not been studied in detail, and readers of this book will be among the first human beings to study some of the ones chosen here." SA

George Musser covers astronomy for Scientific American.

THE EDITORS **RECOMMEND**

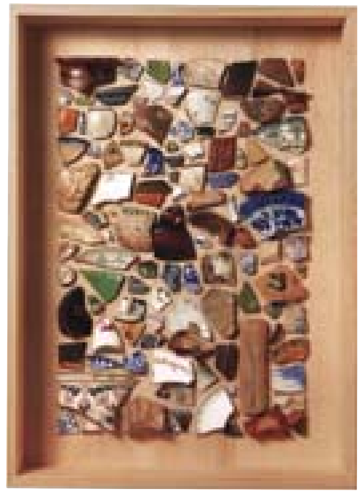
ART FOR SCIENCE

WASTE NOT/WHAT NOT CATALOG
by Gaza Bowen. Cackling Crones Press, Santa Cruz, Calif., 2002 ($10, paperbound)

ARCHAEOLOGY
Edited by Alex Coles and Mark Dion. Black Dog Publishing, London, 1999 ($19.95, paperbound)

MINUS SIXTEEN
by Robin Broadbent. Browns, London, 1998 ($40)

Art has often illuminated science with its brevity, its wit and its beauty. Printed Matter, an organization devoted to making artists' books better known, provides some intriguing recent examples of this contribution. At the "wit" end of the spectrum is Bowen's *Waste Not/What Not Catalog,* a parody of a mail-order catalogue based on her tenure as artist-in-residence at the San Francisco dump. The book mirrors a technological society whose waste is out of control, stunning readers with photographs of what we throw away and introducing them to such concepts as zero waste, cradle-to-cradle design and embodied energy. Artist Dion's archaeology projects—the History Trash Dig, Raiding Neptune's Vault and the Tate Thames Dig—are chronicled in *Archaeology,* which includes a fascinating essay by University of Cambridge archaeologist Colin Renfrew ("It May Be Art but Is It Archaeology?") that analyzes the way Dion dissolves the boundaries between art and science. And there is beauty, too. *Minus Sixteen*—Broadbent's gorgeous, grainy black-and-white photographs of the surface of a Scottish lake, where plunging overnight temperatures create ice layered with alien forms and textures—gives us the universe, as it were, in an ice crystal.

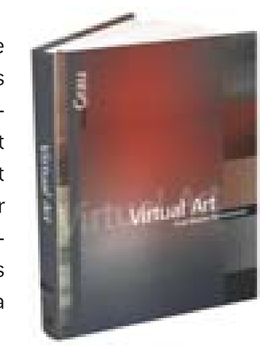


LOOT 2, by Mark Dion (from *Archaeology*)

All available directly from Printed Matter: www.printedmatter.org

VIRTUAL ART: FROM ILLUSION TO IMMERSION
by Oliver Grau. Translated by Gloria Custance. MIT Press, Cambridge, Mass., 2003 ($45)

The computer's ability to immerse a user in virtual image spaces "is not the revolutionary innovation its protagonists are fond of interpreting it to be," Grau writes. "The idea of virtual reality only appears to be without a history; in fact, it rests firmly on historical art traditions." Grau (lecturer in art history at Humboldt University in Berlin, associate professor at the Kunstuniversität Linz in Austria and leader of the German Science Foundation's project on immersive art) traces the lineage of virtual reality as far back as the frescoes of a villa in Pompeii. Many illustrations amplify the argument.



This book and A Traveler's Guide to Mars *are available for purchase through www.sciam.com*

Short Taps

BY DENNIS E. SHASHA

Imagine you are a government official with confidential messages to send. But spies want to intercept the messages. To tap a certain microwave link, your opponents must be in the line of sight of the transmitter. This positioning puts them in danger of detection and arrest, so you are sure they will attempt the job only once and for no more than 10 minutes. The trouble is, you don't know which 10-minute intervals they will choose.

You have seven messages, labeled alphabetically, to send in as short a time as possible. Their lengths are:

- A : 2 minutes
- B : 3 minutes
- C : 4 minutes
- D : 5 minutes
- E : 6 minutes
- F : 7 minutes
- G : 8 minutes

You will accept having the spies intercept up to three of these communiqués. You consider a message to be intercepted if it is tapped from start to finish; a partly tapped message won't do them any good. You must send each message in one continuous transmission, but you can transmit as many as you like in parallel and can begin sending one or more messages while others are still being sent.

To warm up, suppose you can accept the enemy spies' tapping only one complete message. When should you send each message to minimize the total time? See the illustration below for a 36-minute solution.

Because you allow up to three messages to be tapped in the main problem, you may be able to reduce the time considerably. Can you find a way to send the seven messages in 15 minutes or less? If in addition to these seven messages, you had to send three four-minute messages without having more than three of the 10 tapped in their entirety, could you do it in 20 minutes or less? SA

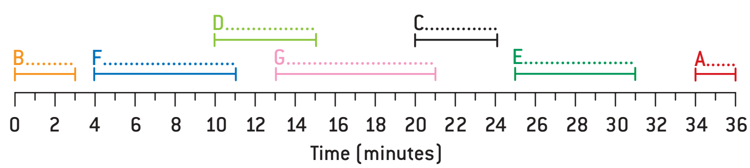
Dennis E. Shasha is professor of computer science at the Courant Institute of New York University. His latest book is Dr. Ecco's Cyberpuzzles: 36 Puzzles for Hackers and Other Mathematical Detectives *(W. W. Norton, 2002).*

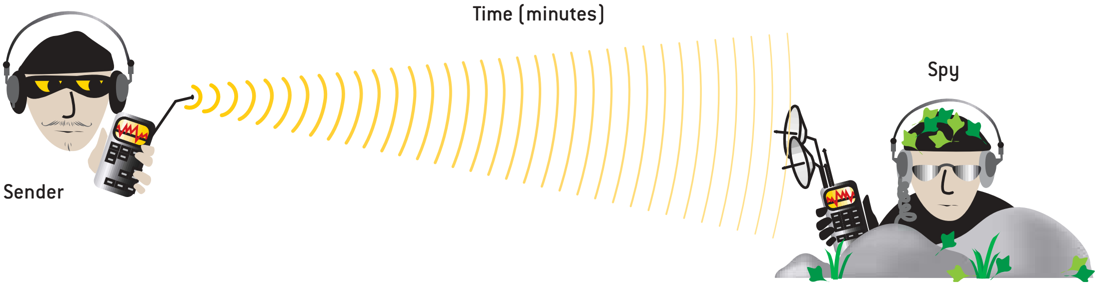
Answer to Last Month's Puzzle

At least one and at most three containers of goods travel from country A to country D. Country E receives at most two containers from A and possibly none. In the second problem, D gets at most three containers from A but possibly none. The minimum and maximum numbers from A arriving at E do not change.

Web Solution

For a fuller explanation of last month's solution and a look at the answer to this month's problem, visit www.sciam.com





CORNELIA BLIK

A WARM-UP SOLUTION

To send all the messages in 36 minutes with no more than one of them getting intercepted, transmit B at 0 minutes, followed by F at 4, D at 10, G at 13, C at 20, E at 25, and A at 34. No 10-minute interval will contain two messages in their entirety. You may be able to discover a better solution.

This Is Only a Test

AN INTERACTIVE LOOK AT SOME RECENT SCIENCE STORIES IN THE NEWS BY STEVE MIRSKY

The dog days of August are upon us. What could be more of a distraction from the summer swelter than the shelter of a familiar exercise ordinarily reserved for the academic year? Therefore, it's time for that old favorite, the true-or-false quiz. (Don't worry, I'll write the essays.)

1. Einstein and Newton may have had a form of autism.

True, according to one autism researcher. *New Scientist* reports that Simon Baron-Cohen of the University of Cambridge thinks that the two great physicists might have had a form of autism called Asperger syndrome. Markers for the syndrome include an obsessive focus on a subject of interest, poor relationships and communication difficulties. (But of course, those symptoms also describe millions of people who listen to hours of sports talk radio every day.) By the way, a newspaper article on Baron-Cohen's theory notes that "firm diagnosis on the dead is impossible," which I disagree with, because rigor mortis is about as firm a diagnosis as there is.

2. A 17-year-old boy in Nuremberg, Germany, is capable of teleportation.

False. The boys claiming to be the possessors of this extraordinary ability were really identical evil twins. One of the twins would demand money from small children, who would turn and flee for a block or so, only to run into what they took to be the very bully they'd just escaped. In May a court told the duplicate delinquents to stop doppelgänging up on people.

3. Scientists proved that an infinite number of monkeys on an infinite number of typewriters will compose the complete works of Shakespeare.

False. But researchers at Plymouth University in England showed that six Sulawesi crested macaques with access to a computer for four weeks at a zoo will produce a tale told by an idiot. According to a May wire service report, the computer was placed in the monkey enclosure, where "the lead male got a stone and started bashing the hell out of it." (A palpable hit.) "Another thing they were interested in," a researcher said, "was defecating and urinating all over the keyboard." (It smells of mortality.) They also pressed the "s" key a great deal for sssssssssome reason. The clacking macaque project was paid for with a grant from England's Arts Council, which will publish the monkey literary efforts as *Notes towards the Complete Works of Shakespeare*. The U.S. National Endowment for the Arts is rumored to be coming out with a companion volume, *Thrilled We Didn't Fund It.*

4. In April the CIA decided to classify a report on a January session in which microbiologists and the CIA's strategic assessment group discussed scientific *openness*.

True. That popping sound was your head exploding.

5. Phosphatase enzymes expedite the breakdown of phosphate monoesters in about 10 milliseconds. Without the enzyme, the reaction's half-life would be a trillion years.

True. Richard Wolfenden, an enzyme maven at the University of North Carolina at Chapel Hill, and his colleagues published that finding in a recent *Proceedings of the National Academy of Sciences USA*. Here's an easy way to appreciate how long a trillion years is. If you paid off the national debt at one dollar a year, it would take 6.4 times as long as the half-life of the enzyme reaction. Fortunately, you don't have to worry about a race between exceedingly slow biochemistry and unbelievably torpid debt relief, because we're lucky enough to have enzymes, and the debt is actually getting bigger.

6. Football players at Giants Stadium in New Jersey run on old sneakers.

True. The stadium's new fake grass is made from recycled sneakers. I learned this listening to sports talk radio. SA

ILLUSTRATION BY MATT COLLINS; PHOTOGRAPH BY FRANK VERONSKY

ASK THE EXPERTS

Would you fall all the way through a hypothetical hole in the earth?

—T. Fowler, Snohomish, Wash.

Mark Shegelski, professor of physics at the University of Northern British Columbia, offers this answer:

Theoretically, yes. For this conjectural trip, let us ignore friction, the rotation of the earth and other complications. Just picture a hole or tunnel that enters the earth at one point, goes straight through the center and comes back to the surface at the opposite side of the planet. If we treat the mass distribution in the earth as uniform (for simplicity's sake), a person could fall into the tunnel and then return to the surface on the other side in a manner much like the motion of a pendulum. Assume that the person's journey began with an initial speed of zero kilometers an hour (he simply dropped into the hole). His speed would increase and reach a maximum at the center of the earth, then decrease until he reached the surface—at which point the speed would again fall to zero. The gravitational force exerted on the traveler would be proportional to his distance from the center of the earth: it is at a maximum at the surface and zero at the center. The total trip time would be about 42 minutes. If there were no friction, no energy would be lost, so our traveler could oscillate through the tunnel repeatedly.

This jaunt could not occur in the real world for a number of reasons. Among them: the implausibility of building a tunnel 12,756 kilometers long, displacing all the material in the tunnel's proposed path, and surviving the journey through a passageway that runs through the earth's molten outer core and inner core—where the temperature is about 6,000 degrees Celsius.

Interestingly, if the tube did not pass through the center of the planet, the travel time would still be about 42 minutes. That is because although the burrow would be shorter, the gravitational force along its path would also diminish compared with that of one that goes through the center of the planet. So the person would travel more slowly. Because the distance and gravity decrease by the same factor, the travel time ends up being the same.

MATT COLLINS

How do manufacturers calculate calories for packaged foods?

—S. Connery, Friday Harbor, Wash.

Jim Painter, associate professor and chair of family and consumer science at Eastern Illinois University, explains:

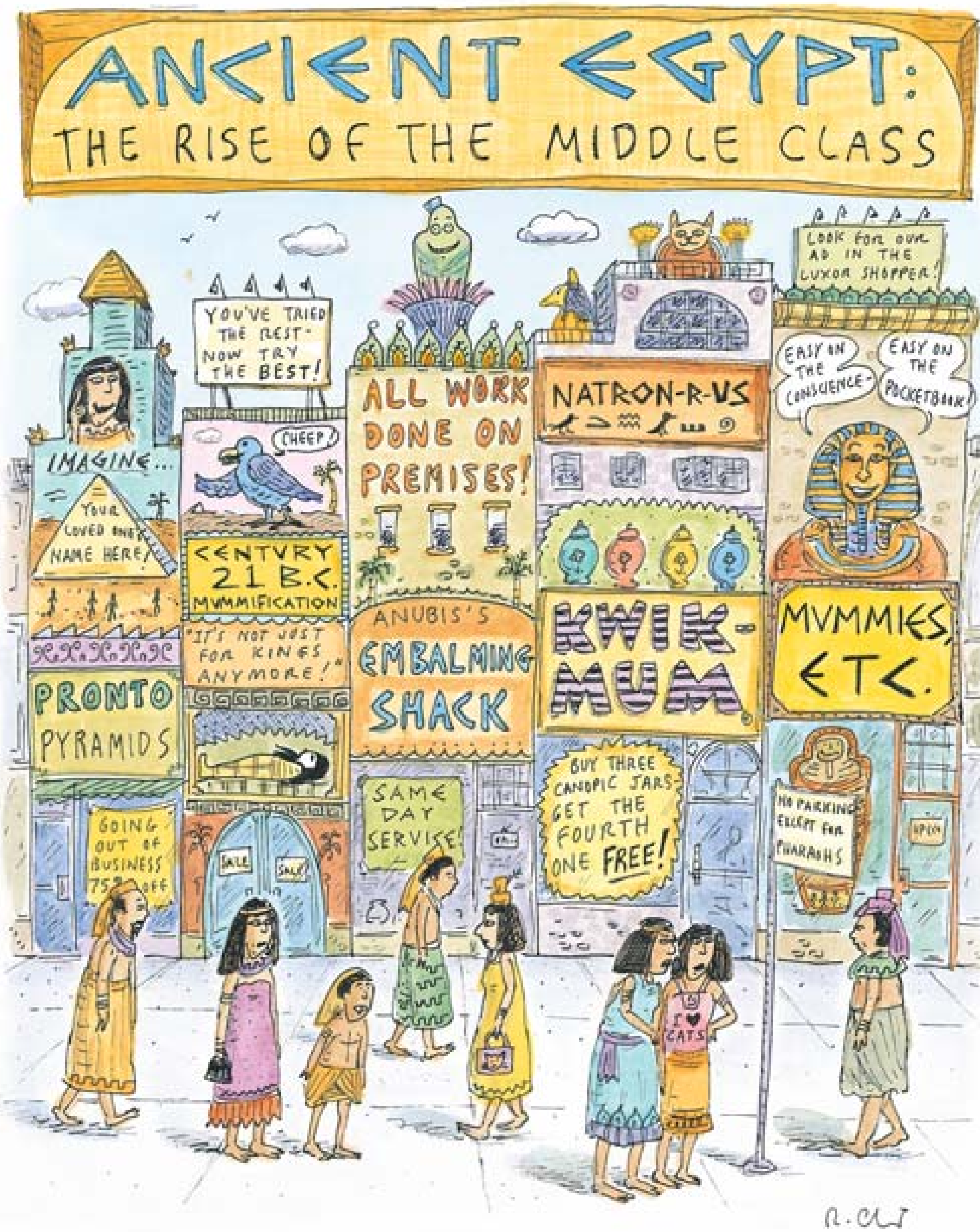
To answer this question, it helps to first define "calorie," a unit used to measure energy content. The calorie you see on a food wrapper is actually a kilocalorie, or 1,000 calories. A Kcalorie is the amount of energy needed to raise the temperature of one kilogram of water by 1 degree Celsius.

Initially, to determine Kcalories, a given food was placed in a sealed container surrounded by water, an apparatus known as a bomb calorimeter. The food was completely burned, and the resulting rise in water temperature was measured. This method, though not frequently used any longer, formed the basis for how Kcalories are counted today.

The Nutrition Labeling and Education Act of 1990 requires that the Kcalories of packaged foods be totaled from the food's energy-containing components: protein, carbohydrate, fat and alcohol. (Because carbohydrates contain some indigestible fiber, the grams of fiber are subtracted as part of the Kcalorie calculation.)

All food labels use the Atwater system, which establishes the average values of four Kcalories per gram for protein, four for carbohydrate, nine for fat and seven for alcohol. Thus, the label on an energy bar that contains 10 grams of protein, 20 of carbohydrate and nine of fat would read 201 Kcalories. Additional information on this subject, and the Kcalorie counts for more than 6,000 foods, is available on the Nutrient Data Laboratory Web site (www.nal.usda.gov/fnic/foodcomp/). SA

For a complete text of these and other answers from scientists in diverse fields, visit www.sciam.com/askexpert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EASY ON THE CONSCIENCE-
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