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SCIENTIFIC AMERICAN

DECEMBER 2006
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3,300,000-Year-Old Baby

What She Means for
Human Evolution

Cracking the
Neural Code

Cancer Clues
from Pet Dogs

The Ultimate
White Light

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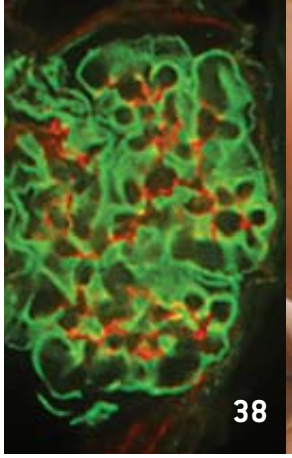

columns

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Old Baby in the New Media

This month's feature article by Kate Wong, "Lucy's Baby," represents something both very old and very new. The old has been christened Selam, a tiny being who was born 3.3 million years ago but did not live past her third birthday. Contrary to the nickname by which she has also come to be well known, Selam was most definitely not a child of Lucy, the *Australopithecus afarensis* female whose skeleton was famously unearthed in 1974—Selam predated Lucy by more than 100,000 years. (Yet incongruity trumps chronology: it seems equally wrong to refer to a baby as "Lucy's grandmother.") Those two australpithecines were probably about as distantly related as any one of us is to the first modern humans to spread out from Africa.

SELAM'S SKULL nestles in a researcher's palm.

REUTERS

But Selam and Lucy are kin as grande dames in the scientific reconstruction of how humans came to walk. Decades ago paleoanthropologists argued about whether our ancient ancestors evolved large brains and then walked erect or became bipedal before they were brainy. The discovery of upright but small-skulled Lucy helped to settle the matter decisively. Now Selam is further illuminating whether *A. afarensis* spent all its time on the ground or, like an ape, still lived a partially arboreal life, as Wong describes, starting on page 78.

So much for the old. What's new about the article is the experimental nature of how it came to be.

The discovery of Selam jumped into headlines around the world this past September. Such momentous, fast-breaking stories can be the bane of monthly print magazines because long publication lead times dictated that we would not be able to share the story with our print readers in any detail until our December issue—an eternity in the 24/7 universe of modern media.

We therefore decided to launch an experiment that we had been contemplating for some time. Kate Wong immediately wrote a news story and posted it on *Scientific American*'s Web site to coincide with the Selam announcement. But that post also invited readers to send us questions and comments, pointing out how they would like to see this story expanded for print. Wong also solicited remarks from leading paleoanthropologists and continued her own reporting.

Thus, *Scientific American*'s coverage of Selam has continued to grow and evolve right up through the December issue deadlines—and will continue to grow after this page goes to press. Distilled into the print version is the best of what has come from this publishing experiment, but we encourage anyone who wants to explore those contents more fully to go to www.sciam.com/ontheweb.

Digital media are already revolutionizing many parts of the publishing industry. Physicists have been sharing preprints of their papers online for more than a decade; now even the professional journals are testing digitally enabled alternatives to traditional peer review. Wikis, social bookmarking and other online exercises in communal authorship have opened eyes to novel ways of creating quality content. We relish the possibilities of this new approach to publication and expect to do much more of it in future issues of *Scientific American*. In the meantime, please tell us what you think about it, too. Your feedback, after all, is what makes this idea work.

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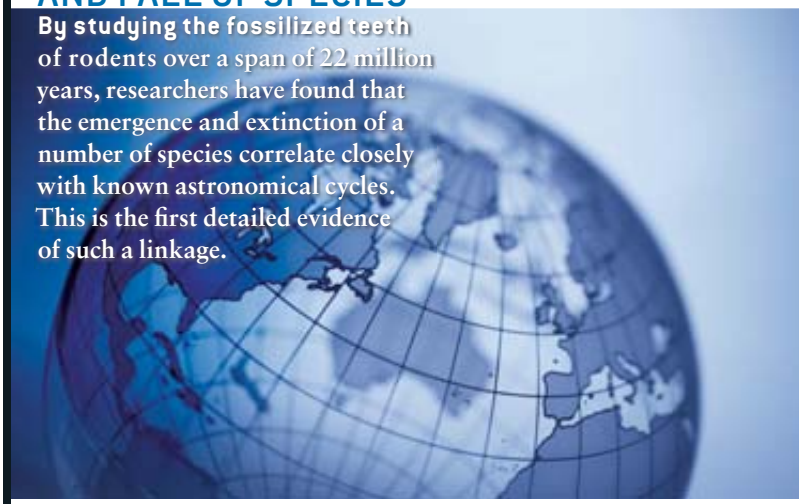
NEWS

EARTH'S TILT SPAWNS RISE AND FALL OF SPECIES



By studying the fossilized teeth of rodents over a span of 22 million years, researchers have found that the emergence and extinction of a number of species correlate closely with known astronomical cycles. This is the first detailed evidence of such a linkage.

CORBIS

Cheating DNA Death

Scientists have uncovered how the extremophile *Deinococcus radiodurans* rebuilds its damaged chromosomes after being bombarded with deadly doses of gamma rays.

Sunless Suntan Proves Possible

Researchers induced tans in mutant mice without exposing them to dangerous ultraviolet rays, suggesting that a similar trick might help even the pastiest among us.

PODCAST

Visit www.sciam.com/podcast to download our free daily and weekly audio programs, *60-Second Science* and *Science Talk*. Recent topics include the genetic basis of a distaste for broccoli, ways to make judges scientifically literate, and the barriers facing women in science.

ASK THE EXPERTS

Why don't magnets work on some stainless steels?
Materials scientist **Thomas Devine** of the University of California, Berkeley, explains.

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Letters

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THE AUGUST ISSUE garnered much interest—that is, vigorous reader dissent, questions and analysis. Although most letter writers welcomed guest essayist Mihail C. Roco's optimistic look at nanotechnology in "Nanotechnology's Future" [Forum], some issued thoughtful caveats about its unforeseen dangers.

The bulk of the dissent, however, was reserved for the cover story "The Expert Mind," by Philip E. Ross, which suggested that studies of the development of chess grandmasters' mental processes may reveal how expertise in all fields is fostered. For those readers who assume that innate ability is the foundation of great achievement, Ross cited research—relating to motivation and the ability to "chunk" information—indicating that experts are made, not born. Much of the criticism was echoed by Doug Jannusch of Kaneohe, Hawaii: "This is an insufficient dismissal of the role of talent in music, chess and sports," its greatest shortfall being "the lack of explanation for the role of intelligence in determining success. Let's face it—some people are simply smarter, faster or stronger than others."

DIMINUTIVE DANGER

Mihail C. Roco describes the "astonishing potential" of nanotechnology in "Nanotechnology's Future" [Forum]. That potential will not be realized, however, unless we take the steps necessary to understand and address its potential impact on human health.

For example, good evidence suggests that the toxicity of some inhaled particles is a function of the surface area exposed to lung tissue. A microgram of nanometer-size particles may be orders of magnitude more toxic than a microgram of micron-size particles. Carbon nanotubes are among the most promising applications of nanotechnology, but in the lung they may mimic another similarly shaped particle—asbestos. Other potential hazards will surely be revealed as the technology progresses.

Sadly, current regulatory agencies are not up to the task. The Occupational Safety and Health Administration can take a decade or more to set a new standard for a single chemical. The Toxic Substances Control Act essentially requires the Environmental Protection Agency to prove that a material is hazardous before it can order a manufacturer to undertake a hazard investigation. Voluntary action by industry and professional organizations can help fill the gap, but our experience with genetically modified food crops shows that the public is unlikely to trust voluntary measures for long.

The hazards will fall most heavily on the workers producing nanotechnology-based products. They deserve protection. The public also deserves protection, along with the amazing benefits that the technology promises. These problems can be solved, but only if we adapt our regulatory systems to promptly uncover and address the risks the technology creates. That task is critical to the future that Roco so ably describes.

Michael J. Wright
Director of Health, Safety and Environment
United Steelworkers
Pittsburgh

SMOKESTACK SELLOUT?

The sidebar, "A Work in Progress," to Gunjan Sinha's "Soccer Goes Green" [News Scan] on the European Emissions Trading Scheme states that "most companies came in far below their limits, rendering their pollution credits worthless." Actually companies that came in below their limits sold their extra allowances and earned windfall profits. A July report from Open Europe estimated that BP, ExxonMobil and Shell made $33.9 million, $19.3 million

and $39.2 million, respectively, assuming they each sold their allowances at an average price of $23 per metric ton. On the buy side were companies that came in above their limits. If countries had set those limits lower, fewer companies would have had surpluses and more investment would have had to have been made in what is the point of the exercise: projects that reduce carbon emissions.

Greg Feldberg
Potomac, Md.

SINHA REPLIES: *Feldberg is incorrect. Open Europe's report projected company profits based on the* assumption *that these companies sold their credits, not on actual sales. So far no evidence indicates that they did; information on the sale or trading of credits is not available to the public at this time. Companies are allowed, however, to carry over their credits through 2007—the end of the first phase of the scheme—so they may stand to earn some profits next year.*

INNATE DEBATE

"The Expert Mind," by Philip E. Ross, presents very interesting results on developing chess expertise and memory retrieval. He gives far too much emphasis, however, to the roles of motivation and training over that of innate abilities. The article goes so far as to claim that intense motivation and training can explain Mozart's genius. That is a startling statement about this incredible child prodigy.

The degree of this downplaying of innate ability is so counter to experience that the burden of strong proof falls on Ross. For example, he must account for child prodigies as well as the numerous fervent aspirants who fail to achieve high mastery after intense training. Although these are informal observations, they cannot be ignored. The article does mention prodigies but in a very conjectural and inconclusive manner.

Ross's support of the contention seems quite unconvincing. He mentions insufficient hard evidence for inherent talent and the lack of correlation between chess ability and visual-spatial abilities. The lack of correlation may suggest a limited understanding of innate ability, not a reason to lower its importance. Are there controlled studies showing that people with the same training and motivation in chess (though otherwise diverse) do not show significant differences in skill mastery? That would confirm the unimportance of innate abilities.

STUDIED GENIUS: New research suggests that motivation and effortful study are more important than innate ability in achieving success in chess, music, soccer and other fields.

The article, though generally interesting, primarily addresses the necessity of training and motivation for chess mastery, not whether these conditions alone are sufficient. Hence, the role of innate abilities would not be exposed. Rather than diminishing the importance of innate ability, it would have been better to state that little is understood about it at present.

Jack Holtzman
San Diego

HALFWAY WRONG

In **"The Geometer** of Particle Physics" [Insights], Alexander Hellemans quotes Alain Connes as saying, "Noncommutative geometry now supplies us with a model of spacetime that reaches down to 10^{-16} centimeter, which still is a long way to go to reach the Planck scale, which is 10^{-33} centimeter." The writer remarks that this is "not quite halfway." In fact, the distances differ by a factor of 10^{-17}. Connes has much further to go: he has gone only one 100-quadrillionth the way.

Anthony Weaver
Department of Mathematics
and Computer Science
Bronx Community College

NOT LOST IN SPACE

In Ask the Experts, Cassini navigation chief Jeremy Jones mentions the accuracy of the calculations available on the ephemerides for the orbits of Saturn's satellites. But do we need them for navigational calculations? The gravitational force exerted by a planet and all its satellites is resumed in its center of gravity, which is what follows its orbit. In the case of Saturn, as well as Jupiter, because the planetary mass so outweighs the total of all satellites, I imagine it is not necessary to correct the observed position for the center of gravity. In this instance, the satellites can be ignored.

Peter Cyrus
Paris, France

JONES REPLIES: *Whether the mass of the individual satellites can be ignored (relying solely on calculating the system mass and barycenter) depends on both the distance from the probe to the satellites and the desired navigational accuracy. If we are dealing with interplanetary navigation, say, a probe going from Earth to Saturn, then for most of the trip we are far from Saturn and the barycenter mass and location can be used without affecting accuracy.*

On the other hand, Cassini orbits Saturn, and we want the best possible accuracy. In this case, Saturn and its major satellites are treated separately. As a part of the overall navigation effort, we estimate both the satellites' orbits and their masses. The minor satellites and the ring mass are very minor contributors (and also poorly known) and are combined with Saturn's mass.

ERRATUM In "Power for a Space Plane," by Thomas A. Jackson, the reference to "latent heat" on page 63 was incorrect. The sentence should instead have spoken of "sensible heat"—whereby the temperature of the liquid increases as it absorbs heat.

ETHAN HILL

50, 100 & 150 Years Ago
FROM *SCIENTIFIC AMERICAN*

Synthetic Elements ▪ First-Flight Rights ▪ Fiery Ship

DECEMBER 1956

ELEMENT 101—"We watched with eyes fixed on a pulse recorder connected to the ionization chamber. An hour went by. The night dragged on toward dawn. The waiting seemed interminable. Then it happened! The recorder pen shot up to mid-scale and dropped back, leaving a neat red line which represented a large ionization pulse—10 times larger than would be produced by an alpha particle. No such pulse had been recorded from natural background radiation in test runs conducted for many days prior to the experiment. It looked highly probable that the pulse was indeed a signal of the hoped-for fission. The vigil continued. An hour or so later the pen recorded a second pulse like the first. We were now confident that we had witnessed the decay of two atoms of element 101—and had added a new member to the roster of chemical elements.—Albert Ghiorso and Glenn T. Seaborg" [*Editors' note: Seaborg had won a Nobel Prize in Chemistry in 1951 for this work.*]

FLEXAGONS—"Mathematics owes a lot to games, and vice versa. There is an engaging little exercise with strips of paper which has fascinated some first-class brains in recent years. It was discovered in an idle moment by a British mathematics student at Princeton University. The whole thing grew out of the trivial circumstance that British and American notebook paper are not the same size.—Martin Gardner" [*Editors' note: This article was Gardner's first of numerous contributions to this magazine, all of which are now available on the CD-ROM "Martin Gardner's Mathematical Games."*]

DECEMBER 1906

FIRST FLIGHTS—"In all the history of invention there is probably no parallel to the unostentatious manner in which the Wright brothers, of Dayton, Ohio, ushered into the world their epoch-making invention of the first successful aeroplane flying machine. Their success marked such an enormous stride forward in the art of flying, was so completely unheralded, and was so brilliant that doubt as to the truth of the story was freely entertained; especially as the inventors refused either to give access to the machine or to make any statement as to its broad details. The SCIENTIFIC AMERICAN, however, wrote to the seventeen eye witnesses who were mentioned as having seen the various flights and received letters from these reputable local residents, which completely set at rest all doubt as to what had been accomplished. Unfortunately, the foreign aeronautical world failed to appreciate the significance of the facts as thus made known; and when Alberto Santos-Dumont made his recent short flight of a few hundred feet he secured in Europe the credit for having made the first successful flight."

DEEP-SEA PEDESTRIAN—"A novelty in the way of diving apparatus is the invention of M. de Pluvy, a prominent hydrographic engineer of Paris. The suit is built of light and strong sheet metal. The joints and coupling points are made of pressed leather and rubber. The air is not brought to the diver from the outside, as usual, but the air he breathes is sent by a tube into a special regenerating chamber containing certain chemical products which renew the supply of oxygen. M. de Pluvy has personally been able to go down as far as 300 feet with the new diving suit."

DE PLUVY DIVING SUIT opens Neptune's realm, 1906

DECEMBER 1856

ETHER PROBLEM—"News from Bahia (South America) gives an account of the burning of one of the combined steam and ether ships, named *La France,* in that harbor. The ether could not be kept in the liquid state in that warm climate; it escaped in great quantities from the tanks in which it was contained, caught fire, and burned up the entire vessel. Ether boils at 96° Fahrenheit, therefore it was exceedingly stupid for those who had charge of that vessel to carry ether with them into such a climate, where the water in the bay often ranges at a temperature of 100°."

FORENSICS

Partial to Crime

FAMILIES BECOME SUSPECTS AS RULES ON DNA MATCHES RELAX **BY SALLY LEHRMAN**

A MATCH MADE IN DNA

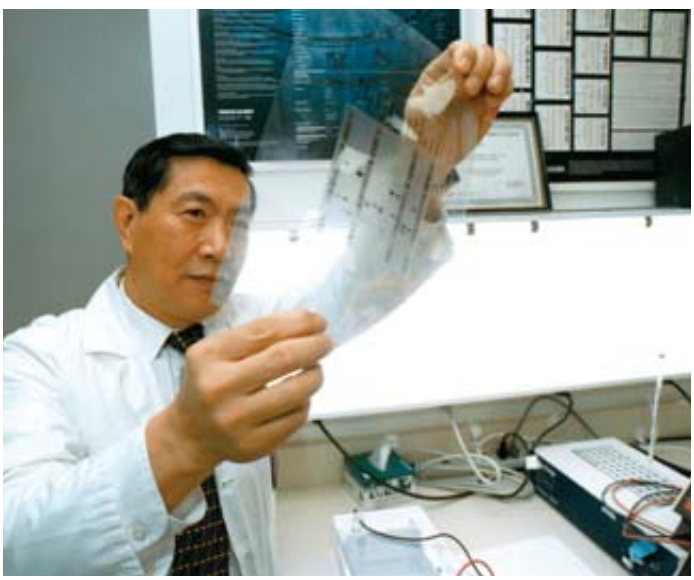
Most forensic DNA tests check for the repetition of short sequences, called short tandem repeats (STR), within 13 areas of the genome likely to differ among individuals. Each person has two possible forms, or alleles, one from each parent. A crime sample is run against the Federal Bureau of Investigation's DNA database to check for matches in the STR pattern at these highly variable locations, or loci. In a "hit," both alleles at all 13 loci look the same.

Sometimes the crime lab must work with as few as 10 loci because of problems with the evidence. To obtain familial or "partial match" information from the national database, investigators must find at least one allele match at each locus. Massachusetts and New York State allow labs to use just four loci for familial and some other searches, potentially implicating far more people.

If a sibling or other close relation of yours ever went to prison for more than a year, suspicion of criminal behavior now extends to you. The Federal Bureau of Investigation recently opened its forensic DNA database of felony offenders and certain other arrestees to allow states to share information that does not exactly match blood, semen or other crime scene evidence but may come close enough to finger a relative. Critics fear, however, that partial matches intrude on privacy and cast suspicion far too widely.

The FBI originally created the Combined DNA Index System (CODIS) in 1990 to help investigators search among convicted sex offenders and other violent criminals for matches to evidence from unsolved crimes. Over the years, its use has rapidly widened to include other types of felons, juvenile offenders and some who committed misdemeanors. Five states can collect DNA from some arrests, whereas federal authorities may acquire biological samples from those who are arrested as well as from noncitizens who are detained. Nationally officials have compiled more than 3.6 million profiles based on 13 regions, or loci, of the human genome that vary among individual people.

When labs can show a match is close



DNA-BASED CRIME FIGHTING as practiced by Henry C. Lee, a prominent forensic scientist based in Connecticut, and others has proved crucial in law enforcement. Rules that relax DNA-matching criteria would put more people under suspicion, especially relatives of convicted people.

STEVE MILLER *AP Photo*

enough to indicate a likely relative—that is, when at least one of the two versions (alleles) of the gene segment at each locus matches up—and there are no other leads, a new interim plan allows states to disclose identifying information on FBI approval. This expansion follows a paper in the June 2 *Science* that outlined the power of indirectly detecting suspects through the database. If only 5 percent of criminals had biological relatives in CODIS, then "cold hit" matches could increase by thousands, the authors of the paper estimated. They pointed to U.S. Department of Justice findings that 46 percent of jailed inmates had an incarcerated relative. "We don't venture whether genetic, social environment, socioeconomic, demographics or whether law enforcement practices account for it," says the lead author, medical geneticist Frederick Bieber of Harvard University. "In a way, it doesn't matter."

By widening its net, law enforcement can move more quickly and potentially head off future crimes, Bieber points out. Critics wonder, however, whether extending genetic surveillance from individuals already associated with crime to their families will help catch enough criminals to outweigh its likely intrusion on privacy and civil liberties. "We're talking about innocent people by proxy being included in this database," objects Tania Simoncelli, science adviser for the American Civil Liberties Union.

Princeton University sociologist Bruce Western questions the premise that familial searches will offer up strong leads, particularly as the databases expand under new laws to include more arrests, detentions and convictions for less serious crimes. In these categories, black and Latino young men are disproportionately pursued and become overrepresented in comparison to their actual share of offenses committed, he explains, and familial searches would magnify these racial and ethnic disparities. In a study of California's largest counties, half of felony charges were later dismissed.

Although family members do tend to share criminal behavior, investigators could use other social patterns of crime to make a comparable argument for searching other groups of DNA profiles—for instance, among males age 16 to 24, people with low levels of schooling, or, for the most violent crimes, people related to the victim. The database operates on a premise that Western says is severely at odds with criminological research—that of criminality as a permanent trait.

"We're kind of blundering ahead with this technology," worries William Thompson, a criminologist at the University of California, Irvine, who would like to see the government open up the database for independent scrutiny and statistical analysis. He is especially concerned about reports of faked test results and poor-quality lab work such as cross-contamination and sample mix-ups.

Also, statistical probabilities for unique matches and assumptions about the database population have recently come into question. Arizona compared felons already in its database and reported 20 "hits" between offenders where both alleles matched at 10 loci. Only three would be expected based on established calculations. The extras could be relatives or even entirely coincidental matches.

Bieber cited two high-profile cases in which investigators used partial matches to narrow in on a perpetrator who was a brother or uncle. But unless the shared alleles are quite rare or the matches are extremely close, this approach can be very inefficient. So Bieber suggested the type of kinship analysis and weighted allele probabilities used to connect family members with loved ones lost in the World Trade Center attacks. CODIS software does not allow for such sophisticated searches at the moment, but Bieber predicts an upgrade as soon as investigators see the potential and define clear statistical thresholds that must be met.

Sally Lehrman, based in the San Francisco Bay Area, wrote about DNA testing of genocide victims in the September issue.

ENTOMOLOGY

Organic Mystery

BT PESTICIDE MAY NOT REALLY BE AN INSECT KILLER **BY DAVID BIELLO**

Nichole Broderick thought she knew how Bt toxin worked. After all, the toxic crystal produced by the bacterium *Bacillus thuringiensis* has been known since at least 1911 and widely used as an organic insecticide since the 1950s. Scientists have even genetically engineered various crops to produce the pesticide. According to the accepted model, Bt toxin punches holes in an insect's gut. These pores either allow the bacterium to infect the insect's blood, the so-called hemolymph, or cause the insect to starve.

So when the University of Wisconsin–Madison graduate student fed the pesticide to gypsy moth caterpillars that had been cleared with antibiotics of other gut bacteria, she expected it to become even more lethal. "Initially I was testing the hypothesis that the gut bacteria were actually protecting the moth from Bt," she recalls. "I found that once they did not have a gut community [of bacteria], I could no longer kill them with Bt."

That Bt might not be an insecticide on its own would overturn a century's worth of orthodoxy, however. So Broderick ran the experiment several times and sought the advice of microbial ecologist Jo Handelsman and entomologist Ken Raffa, both also at Wisconsin. But the researchers all got the same result in multiple insects and multiple trials. Bt toxin worked best when gypsy moth stomachs hosted their normal complement of bacteria.

Studies on Bt in the past decades have focused on the first steps of Bt's action. "Nobody has really focused on what happens after the toxin makes the holes and the cells die," comments entomologist Juan Jurat-Fuentes of the University of Tennessee–Knoxville. "Do the insects recover, or are the other bacteria taking over?" The Wisconsin researchers found, by reintroducing the gut bacteria one by one, that the *Enterobacter* species NAB3 reinstated Bt's deadliest impact, and subsequent tests showed that this bacterium thrived in the hemolymph, whereas *B. thuringiensis* quickly died. Further, *Escherichia coli* engineered to produce the Bt crystal proved equally effective in killing larvae, although not when the bacterium host was dead but still carrying the toxin.

The results may explain the variable effectiveness often seen in Bt; for example, gypsy moths feeding on willow are resistant to the toxin, Raffa notes. Some had argued that the tannins in the willow might be binding to the Bt protein and allowing it to be eliminated, but now Raffa wonders if other compounds in the tree might be affecting *Enterobacter,* which might be the true killer. "Where it gets to be important is in revisiting our interpretation of some of those earlier findings," he says. It also might help explain the mystery of corn pest *Spodoptera frugiperda,* more commonly known as the fall armyworm, which develops holes in its gut when exposed to Bt but fails to die. "People had a hard time explaining how this toxin binds and makes pores, but it's not killing the insects," Jurat-Fuentes says.

B. thuringiensis is also rather mysterious: it remains unclear why the bacterium expends so much energy produc-

TOXIC BUG ***Bacillus thuringiensis*** **produces a crystal widely used as a pesticide. Precisely how the crystal kills remains mysterious.**

SciMAT *Photo Researchers, Inc.*

ing the crystals, as it delivers no clear benefit to the microbe. And after roughly 10 years of widespread use in transgenic crops—globally, at least 500,000 square miles of farmland bear plants that produce their own Bt toxin—almost none of the targeted insects have shown signs of immunity, unlike other pesticides. "There is still only one insect, the diamondback moth, that has evolved resistance," observes entomologist Bruce Tabashnik of the University of Arizona.

Although this study suggests that Bt works in conjunction with gut bacteria, perhaps to produce septicemia, the exact killing mechanism remains unknown. Resolving it could lead to ways that prevent Bt resistance or improve the effectiveness of the toxin. At least the research gives new appreciation of the crop pests. "More and more we're seeing that you can't just think of the insect as a single species," Tabashnik remarks. "You have to look at the community of the symbionts it harbors and how that affects how it interacts with its environment."

MATERIALS

Call It Beetle Guard

BUG-BASED COATING COULD NEUTRALIZE TOXINS **BY MARK FISCHETTI**

The African Stenocara beetle has become mildly famous for using its wings to capture vapor molecules in the parched Namib Desert air and to herd them into a droplet that rolls into its mouth. Now two Massachusetts Institute of Technology professors have devised a material that mimics this action and goes a step further, which may lead to a range of long-anticipated products that manhandle fluids.

Chemical engineer Robert E. Cohen and materials scientist Michael F. Rubner seeded a polymer thin film with rows of silica nanoparticles and coated the surface with a fluorinated chemical that aggressively repels water. They then attached acid molecules to the nanoparticles, forming rows of nodes (like lights lining the sides of airport runways) that strongly attract water. Vapor molecules run off the hydrophobic runways and coalesce into droplets at the hydrophilic nodes. As the droplets grow, they fuse and run off in straight channels to be collected at the film's edge.

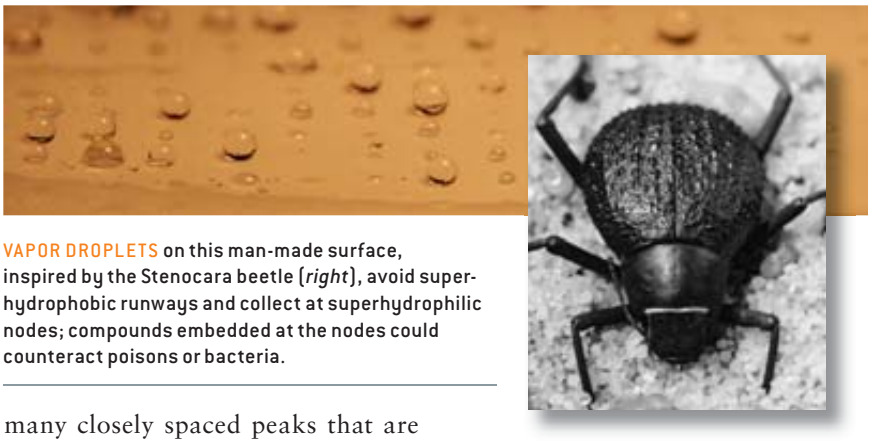
A host of applications are possible at this level alone. Coated sailcloth could be hung in desert regions, channeling humidity into a collection vessel for drinking water. The material could also harvest dew. Garments of all kinds could be made extremely stain resistant. "We treated a lab coat, then poured hot coffee on it, and the coffee rolled right off," Rubner says.

Yet even more sophisticated products could arise. The researchers are trying to implant compounds in the runoff channels that could neutralize chemical and biological agents as they were repelled by military clothing or that could kill bacteria that might collect on hospital surfaces. Small biochips that could perform rapid medical tests in doctors' offices are also in their sights. "We are looking at an array of chemistries that could detect DNA or viruses and screen for many diseases at once," Rubner explains.

Better antifog coatings might result, too. Goggles, windshields, even surgical endoscopes fog when minuscule vapor droplets do not coalesce and run off. "Of course, I've already received a call from a paintball guy who wants a safety mask that won't fog from heavy breathing," Rubner says.

Plenty of challenges stand between a lab material and practical products. Under a microscope, the hydrophobic region resembles a mountain range with

Mission Control



VAPOR DROPLETS on this man-made surface, inspired by the Stenocara beetle (*right*), avoid superhydrophobic runways and collect at superhydrophilic nodes; compounds embedded at the nodes could counteract poisons or bacteria.

MICHAEL RUBNER AND ROBERT COHEN *Massachusetts Institute of Technology (droplets);* ANDREW PARKER *University of Oxford and the Natural History Museum (beetle)*

many closely spaced peaks that are capped with the fluorine compound. Repelled vapor molecules roll across the peaks, supported by the air in the valleys. "Air-laden surfaces like these are not particularly strong," Rubner notes, and could be wiped off if rubbed too hard. He and Cohen are trying to fabricate hilltops with glass nanoparticles, which would be more durable. Designing surfaces that can be cleaned is another issue; if dirt or hazardous agents collect in the valleys, abrasive cleaners could wear off the coating, and liquid-base cleaners might just roll off instead of scouring out the grime. "In the real world," Rubner acknowledges, "all kinds of stuff will be thrown at these surfaces."

PSYCHOLOGY

Voting with the Heart

EMOTION TRUMPS REASON AT THE BALLOT BOX

BY CHARLES Q. CHOI

Citizens thoughtfully weigh the pros and cons of arguments before choosing their leaders—or so political science has traditionally assumed. Now experiments and computer models are challenging this notion, suggesting that voters tend to make emotional decisions that they rationalize afterward.

Such is the conclusion of political scientist Charles Taber of Stony Brook University and his colleagues, who have examined during the past 10 years how people decide whom they vote for. "Politics, like religion and war, is all about emotions and feelings," Taber says. "The enlightenment model of dispassionate reason as the duty of citizenship is empirically bankrupt."

In their experiments, Taber and his colleagues asked undergraduates to give positive or negative responses as quickly as they could to target words shown on a computer, such as "beautiful" or "horrible," each laden with unambiguously good or bad undertones. Before each target was displayed, the researchers flashed a subliminal cue word on the screen for 200 milliseconds, too fast for volunteers to notice consciously. Cues with positive connotations such as "sunshine" generally sped up response times for targets with good undertones, whereas negative cues such as "cancer" slowed them down. The opposite was seen for targets with bad undertones.

The researchers also employed cues with political undertones, including people, groups or issues such as "Lincoln" or "gun control." They found students' reaction times went up or down depending on whether they rated the political cues positively or negatively in a survey given after the experiment. "The implications are that there

VOTERS (here in Paris, France) may rely more on emotion than reason to make their choices.

are things outside our awareness that can significantly affect your reactions to the world in a pretty politically relevant way," remarks political psychologist Richard Lau of Rutgers University.

In recent experiments, Taber and his coworkers flashed cues that were linked with groups with which the volunteers were affiliated—for instance, "black" or "Democrat." They found the students were more likely to support political issues popularly linked with their own groups, such as "affirmative action" in this example. The opposite proved true if volunteers were cued with groups not their own. Similar findings were seen when volunteers were cued with just the words "we" or "they."

"The power of these automatic effects is startling and counter to traditional models where we deliberate over ideas," Taber says. Instead, he argues, people make their decisions nearly instantly after exposure to political cues, and the conscious thinking afterward rationalizes their emotional response. "It's not that reasoning doesn't happen, but it's just very heavily influenced by automatic reactions to things as simple as 'us' or 'them,'" Taber remarks. This is consistent with decades of surveys that reveal that citizens' political orientations or demographics matter much more than how well informed they are about a candidate.

Based on their theories, the scientists developed a computer model dubbed John Q. Public to simulate political opinions of voters on current events. They constructed 100 virtual voters, each programmed into different political groups with unique mindsets regarding terms such as "president," and ran the model on the TeraGrid supercomputer network, which spans nine U.S. supercomputing sites.

These simulated citizens were fed newspaper accounts of debates and conventions during the 2000 election campaign, which were boiled down to simple sentences, such as "Bush said Bush is antiabortion," to make them easier for the program to process. The voters' responses to these statements, either positive or negative, almost perfectly matched trends found in actual 2000 national polling data of 100,000 Americans, submitted to the *American Journal of Political Science*.

Taber could imagine "how our findings could be used for a greater understanding of how to manipulate people. I hope that wouldn't be how it's used." Still, politicians have swayed public opinion with patriotic symbols, upbeat music and similar cues for millennia. "Aristotle talked about it. Real politicians have always known people are less thoughtful than emotional," Taber adds, noting that the best way to counteract such manipulation is to be aware of it.

Charles Q. Choi is a frequent contributor.

POLITICS AND RACE

Charles Taber of Stony Brook University and his colleagues are also looking at how race affects political behavior. According to Taber and others, many political scientists believe that overt racism no longer plays a major role in politics today. Political conservatives who oppose affirmative action and other race-linked policies, the thinking goes, say they are driven by principles such as a Protestant work ethic. But Taber's preliminary data suggest otherwise: race-linked terms such as "hip-hop" are recognized more easily and automatically from jumbles of letters when prompted by subliminal cue words such as "affirmative action."

OWEN FRANKLIN *Corbis*

Send in the Terminator

A MICROSOFT TOOL LOOKS FOR PROGRAMS THAT FREEZE UP **BY GARY STIX**

Alan Turing, the mathematician who was among the founders of computer science, showed in 1936 that it is impossible to devise an algorithm to prove that any given program will always run to completion. The essence of his argument was that such an algorithm can always trip up if it analyzes itself and finds that it is unable to stop. "It leads to a logical paradox," remarks David Schmidt, professor of computer science at Kansas State University. On a pragmatic level, the inability to "terminate," as it is called in computerese, is familiar to any user of the Windows operating system who has clicked a mouse button and then stared indefinitely at the hourglass icon indicating that the program is looping endlessly through the same lines of code.

The current version of Microsoft's operating system, known as XP, is more stable than previous ones. But manufacturers of printers, MP3 players and other devices still write faulty "driver" software that lets the peripheral interact with the operating system. So XP users have not lost familiarity with frozen hourglasses. The research arm of Microsoft has tried recently to address the long-simmering frustration by focusing on tools to check drivers for the absence of bugs.

Microsoft Research has yet to contradict Turing, but it has started presenting papers at conferences on a tool called Terminator that tries to prove that a driver will finish what it is doing. Computer scientists had never succeeded until now in constructing a practical automated verifier for termination of large programs because of the ghost of Turing, asserts Byron Cook, a theoretical computer scientist at Microsoft Research's laboratory in Cambridge, England, who led the project. "Turing proved that the problem was undecidable, and in some sense, that scared people off," he says.

Blending several previous techniques for automated program analysis, Terminator creates a finite representation of the infinite number of states that a driver could occupy while executing a program. It then attempts to derive a logical argument that shows that the software will finish its task. It does this by combining multiple "ranking functions," which measure how far a device driver has progressed through the loops in a program, sequences of instructions that rerun until a specified condition is met. Terminator begins with an initial, rather weak argument that it refines repeatedly based on information learned from previous failed attempts at creating a proof (a sufficiently strong argument). The procedure may consume hours on a powerful computer until, if everything goes according to plan, a proof emerges that shows that no execution pathway in the driver will cause the dreaded hourglassing.

Terminator, which has been operating for only nine months and has yet to be distributed to outside developers of Windows device drivers, has turned up a few termination bugs in drivers for the soon-to-be-released Vista version of Windows while trying to come up with a proof. Cook predicts that Terminator may eventually find proofs for 99.9 percent of commercial programs that finish executing. (Of course, some programs are designed to run forever.) Turing, however, can still rest in peace. "There will always be an input to Terminator that you can't prove will terminate," Cook says. "But if you can make Terminator work for any program in the real world, then it doesn't really matter."

Patrick Cousot of the École Normale Supérieure in Paris, a pioneer in mathematical program analysis, notes that Terminator should work for a limited set of well-defined applications. "I doubt, for example, that Terminator is able to handle mathematically hard termination problems"—those for floating-point numbers or programs that run at the same time. Cook does not disagree, saying that he plans to develop termination proof methods for such programs. Finding a way to ensure that more complex programs do not freeze is such a difficult challenge, however, that Cook thinks it could consume the rest of his career.

TIME & LIFE PICTURES *Getty Images*

ALAN TURING created a mathematical proof that explains the uncertainty of any computer program ever completing a task.

COMPUTER ENTOMOPHOBIA

Worldwide, software bugs cost billions of dollars in losses every year, which explains a trend among companies for automated program verification. In 2005 Microsoft released an automated bug-catching program, Static Driver Verifier, that checks the source code for device drivers against a mathematical model to determine whether it deviates from its expected behavior.

Static verifiers look for programming errors that cause a program to stop its execution. A device driver, for instance, should never interact with program B before it has done so with program A, or it will simply cease operation. Terminator, Microsoft's latest tool, looks for mistakes that may lead a program to continue running forever in an endless loop, thereby preventing it from finishing the job at hand.

OPTICS

Looking Better

ADVANCED LIGHT MICROSCOPY FOR THE RESEARCH MASSES

BY EMILY HARRISON

Sitting by his laptop on the Mission Bay campus, Orion Weiner of the University of California, San Francisco, is watching a movie of an immune cell called a neutrophil scurrying across his computer screen. The movie, made with a conventional optical microscope, reveals that a fuzzy vanguard of proteins is driving the neutrophil. But when he opens a second movie file of the motion, this one made with a more advanced light microscopy technique called total internal reflection fluorescence (TIRF), the vanguard no longer appears as one solid front of proteins but rather as a wave of individual proteins pushing forward like ripples from a pebble in a pond.

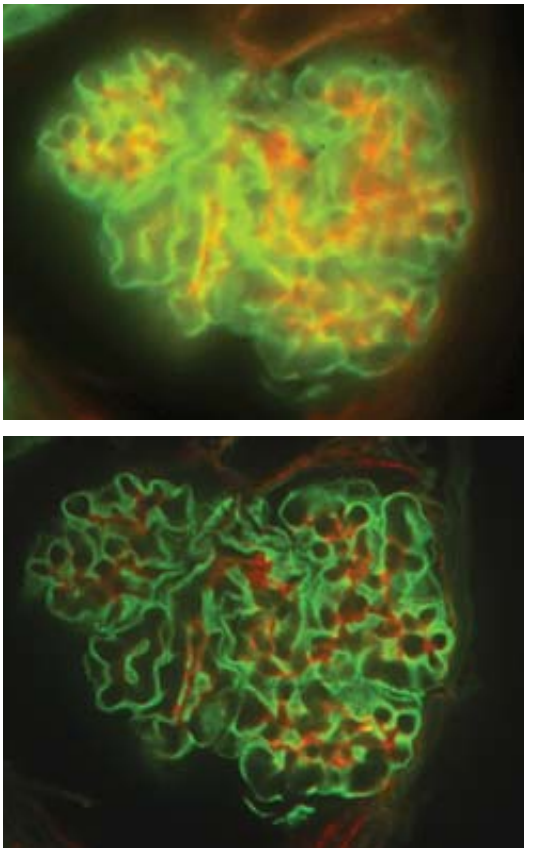
Weiner never expected to find this robust wave motion, and until recently, he would not have been able to visually capture it using a light microscope. And even now that the technology to do so exists, such advanced tools are typically limited to the very fortunate and few. At U.C.S.F., there is a plan to change that.

Weiner is one of the many researchers who will benefit from the U.C.S.F. Nikon Imaging Center for advanced light microscopy that opened there this fall. A collaboration between U.C.S.F. and the California Institute for Quantitative Biomedical Research (QB3) with Nikon Instruments, the center aims to fuel both biological discovery and continued development of microscopy technologies by putting six state-of-the-art optical microscopes into the hands of a wide range of faculty and postdoctoral and graduate students.

For many decades, the resolution and detection limitations of conventional optical microscopy made it nonideal for many aspects of quantitative biology. To explore nanometer-scale structure, scientists instead turned to high-resolution techniques such as electron microscopy. To quantify the presence of particular molecules in samples, they broke apart many cells and averaged the quantities of the various components in question.

Missing was the ability to see how all the pieces of the cells worked together. "Traditionally, biochemistry has been doing everything in test tubes with ideally purified proteins," says Ron Vale, a U.C.S.F. biologist who has long incorporated cutting-edge microscopy into his research. "As we look forward, we would like to understand the biochemistry—that is, reactions that are happening, proteins that are touching and coming off from one another, and how that's all happening in the complexity of a cell with 10,000 different proteins in it."

The six microscopes at QB3 achieve their high performance thanks to advancements in different disciplines. Protein engineers have developed fluorescent molecules based on the jellyfish protein GFP, which can be genetically incorporated into sam-



KIDNEY SECTION seen in widefield fluorescence (*top*) lacks detail compared with a technique that blocks out extraneous light (*bottom*).

JENNIFER WATERS *Harvard Medical School Nikon Imaging Center*

BEYOND PICTURES

Crucial to the development of high-resolution microscopy are the computers associated with the devices, which can process terabyte-size image files overnight and organize them into tidy image galleries. In the minds of some scientists the real future of microscopy lies not in prettier pictures but in the computational modeling of massive quantities of data, says Wallace Marshall, an electrical engineer in the department of biochemistry and biophysics at U.C.S.F. who uses optical microscopy to examine how cells solve engineering problems, such as how many organelles to make and how big.

ples for very specific tagging. Innovations in optics and electronics have led to microscopes equipped with electron-multiplying, charge-coupled devices able to detect extremely low fluorescence and maximize the signal-to-noise ratio in electronic images. Such sensitive light collection lets researchers generate images very fast or at very good resolutions, depending on the needs of the study.

Other advancements have improved stability, allowing investigators to lock samples in focus and create a time lapse from images collected over several days. And some older techniques have found new life in the presence of these innovations, among them TIRF microscopy. In this technique, light strikes the coverslip at such an angle that it is totally reflected. The process creates so-called evanescent light waves, which decay exponentially and disappear within about 100 nanometers. The evanescent waves can thus be used to target specific fluorescent tags without illuminating the rest of the sample. Because it does not create much spillover light, TIRF can take optical sections six times thinner than fluorescence confocal microscopes, the previous resolution champion.

As advanced as the microscopes in the imaging center are, the next wave is brewing just down the hall. Mats Gustafsson, a U.C.S.F. physiologist, is working on techniques that may resolve details down to 40 nanometers—5.5 times finer than the absolute limit of the conventional light microscope. Combined with other fine techniques, such as single-molecule detections that can report spatial distances as small as two nanometers, such advances will bring a deeper understanding of cell systems to light.

Yogi Berra, the pithy baseball great, said, "You can observe a lot just by watching." Thanks to the collaboration among Nikon, U.C.S.F. and QB3, researchers will be observing a lot more.

PHYSICS

Light-Matter Teleportation

Physicists recently teleported information stored in a beam of light into a cloud of atoms, without destroying the sensitive quantum state, a feat essential for future quantum computers and cryptography systems. Eugene Polzik and his colleagues at the Niels Bohr Institute in Denmark first entangled the laser and atoms into sharing a complementary quantum state by shining a strong laser beam onto a cloud of cesium atoms.

A second weak laser pulse, which stored the information to be teleported, was then mixed with the strong light beam, and their combined amplitudes and phases were measured. The researchers used the results to alter the quantum state of the cesium cloud to match that of the weak pulse. Effectively, the quantum state was transferred, or teleported, between the two, the scientists report in the October 5 *Nature*. —*JR Minkel*

PSYCHOLOGY

Brain Zaps for Generosity

In the ultimatum game two players are offered a set amount of money. If they agree on how to divvy it up, they will keep that money for themselves. If they don't, neither will get anything. The game pits selfish impulses against social norms of fairness. Researchers at the University of Zurich recently found that damping activity in the prefrontal cortex region of the brain can set free our selfish side using transcranial magnetic stimulation (TMS), which alters the firing of neurons in the area where it is applied. Almost 45 percent of men who experienced TMS on the right side of their prefrontal cortex accepted the most unfair offers in the ultimatum game. In comparison, about 15 percent of those whose left side had been stimulated and around 9 percent of the control subjects that did not receive TMS accepted inequitable offers. *Science* published the findings online on October 5. —*David Biello*

BIOTECH

Blood Blocker

Bleeding on the battlefield and in routine surgery is controlled by a number of different products, all of which have drawbacks, such as the potential for excessive heat, blood clots and allergic reactions. But a new biodegradable protein solution able to stanch bleeding in mere seconds appears to also be nontoxic and long-lasting in animals. Researchers at the Massachusetts Institute of Technology and the University of Hong Kong developed a liquid made from short proteins, or peptides, that could repair severed optic nerves in hamsters and control brain bleeding in mice, as well as oozing from other types of wounds. The liquid apparently formed a fibrous network over the wound that stopped bleeding, although how the material works in detail is unclear. The liquid does not seem to form a conventional blood clot, the group notes in a study published online October 10 in *Nanomedicine*. —*JR Minkel*

BLEEDING could be stopped in seconds with a new protein liquid.

ICONICA Getty Images

BRIEF POINTS

- **A bacterium living inside an insect has the tiniest genome known, consisting of just 160,000 base pairs that make up at most 182 genes. It may reflect an organelle in the making.**

  Science, October 13

- **The carnivorous dinosaur *Coelophysis bauri* was long thought to be a cannibal based on fossils showing its own species' bones in its stomach. But a reanalysis suggests that the bones probably represent an intermingling after death.**

  Biology Letters online, September 19

- **Indonesian wonders: The so-called Bird's Head Seascape off the western coast of New Guinea revealed after a recent survey that it contained as many as 52 new species of fish, shrimp and coral.**

  Conservation International announcement, September 18

- **Time to make the doughnuts: An expulsion of protein from the cell nucleus seems to be at the root of familial advanced sleep phase syndrome, a rare condition in which people hit the hay and wake up about four hours before everyone else.**

  Genes and Development online, September 18

Extended coverage of these News Scan briefs can be found at ***www.sciam.com/ontheweb***

THE 2006 NOBEL PRIZES

On December 10, Alfred Nobel's wish to recognize the contributions of scientists whose work confers "the greatest benefit on mankind" will be honored for the 105th time. The Royal Swedish Academy will present this year's Nobel Prize laureates with their prize, including medals and diplomas, at a ceremony in Stockholm. For more details, visit www.nobelprize.org.
—Alison Snyder

PHYSICS: John C. Mather of the NASA Goddard Space Flight Center and George F. Smoot of the University of California, Berkeley, for their research during the 1980s on the form of the cosmic microwave background radiation that was released early in the big bang.

CHEMISTRY: Roger D. Kornberg of Stanford University, for his work over the past six years illustrating the molecular mechanism for copying genes in eukaryotes.

PHYSIOLOGY OR MEDICINE: Andrew Z. Fire of the Stanford University School of Medicine and Craig C. Mello of the University of Massachusetts Medical School, for their 1998 discovery of RNA interference, which regulates gene expression and helps defend cells against viruses.

ECONOMICS: Edmund S. Phelps of Columbia University, for his work in the 1960s elucidating the relation among unemployment, inflation and expectations, thereby better connecting current policy and future economic goals.

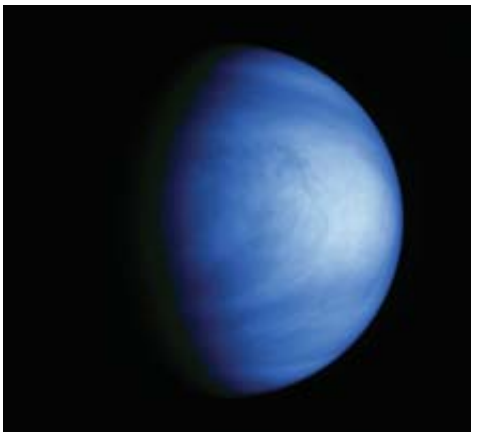
ASTRONOMY

A Reason for a Moonless Venus

One of biggest mysteries in the solar system is why Venus has no moon. A new model proposes that our sister planet may in fact have had a moon but that it was destroyed. At an October meeting of the American Astronomical Society, Alex Alemi and David Stephenson of the California Institute of Technology suggested Venus underwent not one large impact, like the collision thought to have formed Earth's moon, but two. The first caused the planet to rotate counterclockwise and created a moon that began to drift away. But a second impact sent Venus spinning clockwise, canceling the effect of the first collision. This reversal changed the gravitational interactions between the moon and planet and caused Venus's moon to start moving inward, ultimately colliding with the planet. The second impact may or may not have created a moon, too. If it did, this moon would have been swept up by the first one on its inward plunge toward doom.

—George Musser

NO MOON HERE, but Venus may have had one once.



BIOLOGY

Moles' Cancer Brake

Most moles harbor mutations that can trigger deadly skin cancer, but many do not fulfill any cancerous destiny. Researchers at the University of Michigan at Ann Arbor pinpointed a series of mechanisms that prevent cells in a particular type of mole from continuing to divide, despite having various mutations and tumor-promoting oncogenes. The scientists found that the endoplasmic reticulum, the organelle inside cells that folds amino acids into proteins, can sense the presence of oncogenes and stop its protein folding, thereby shutting down the cancerous cell prematurely.

MOST MOLES do not progress to cancer.

While this mechanism protects against tumor growth, tumor cells could take advantage of this state—not dead but no longer dividing—"to favor survival and resistance to drugs," researchers note in the October issue of *Nature Cell Biology*. In other words, the internal mechanisms can both help guard against cancer as well as help promote its growth. *—David Biello*

EXTINCTIONS

Earth's Precession, Species Procession

Mammal species do not seem to last very long in the grand scheme of things, persisting for an average of 2.5 million years, according to the fossil record. By studying the fossilized teeth of rodents from over a span of 22 million years, Jan van Dam of Utrecht University and his colleagues found that rodent species rise and fall in cycles that closely match variations in Earth's orbit. The cycle between an elliptical and circular orbit and a change in the tilt of Earth's axis combined to create periods in which our planet did not tilt very much as it revolved around the sun, thereby eliminating seasons and resulting in less climatic variability. "These climate changes may destroy the habitat of rodents or give new rodent forms a chance," van Dam says. The finding appears in the October 12 *Nature*. *—David Biello*

NASA/JPL (*top*); BSIP, CHASSENET *Photo Researchers, Inc.* (*bottom*); AP PHOTO (*Nobel medal*)

BY THE NUMBERS

Not So Revolutionary

RECENT ADVANCES ARE NO THIRD INDUSTRIAL REVOLUTION **BY RODGER DOYLE**

A widespread notion is that computers, the Internet, nanotechnology, bioengineering, and so forth represent a fundamental change in human affairs. These recent inventions are sometimes hailed as a "third Industrial Revolution." The first Industrial Revolution—roughly spanning the 1770s to 1860s—saw the development of the steam engine, steamboat, locomotive, telegraph, cotton gin and steel plow. The second Industrial Revolution—from the 1870s to the 1910s—witnessed the invention of the telephone, internal-combustion engine and electric lightbulb as well as the germ theory of disease, movies and radio.

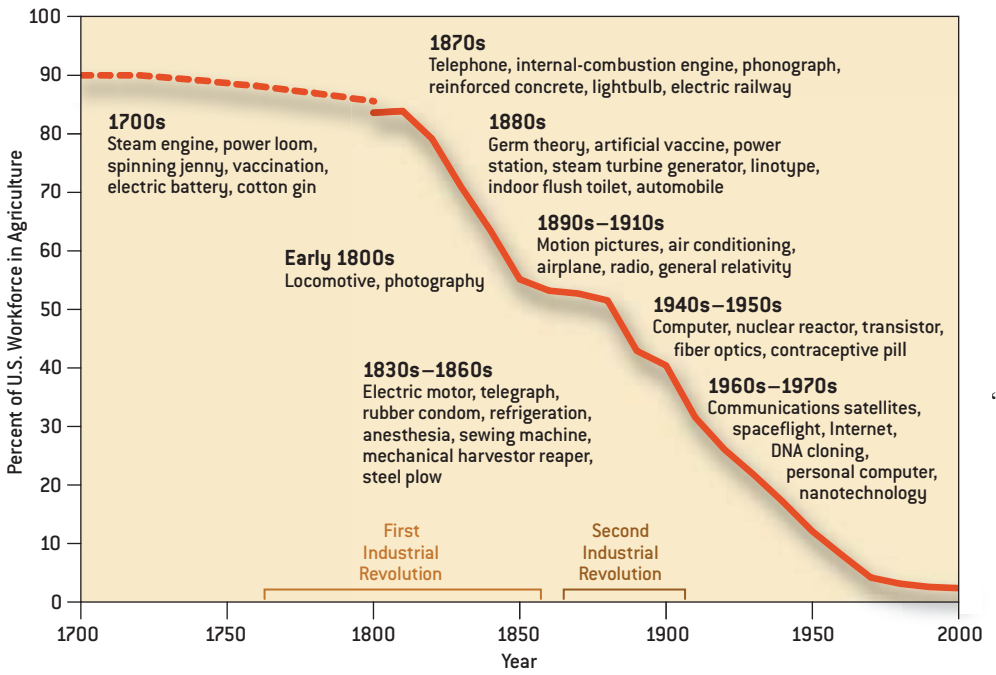
The first and second Industrial Revolutions vastly increased farm productivity, thus increasingly freeing the labor force to work in other occupations. By eliminating farming as the main occupation of Americans, as the chart shows, these inventions eventually led to the liberalization of sexual mores and the emancipation of women. Agricultural societies need child labor, so fertility is all-important. Anything that interferes with childbearing, such as divorce, homosexuality and abortion, is strongly discouraged.

In industrial societies, these taboos fade as infant and child mortality decline, lessening the pressure on women to reproduce. Marriage is delayed as higher education is emphasized. Increasingly, women hold jobs previously held only by men. Moral prescriptions against premarital sex begin to fade, a phenomenon apparent even before availability of the contraceptive pill in the 1960s. Nothing comparable to these changes has happened as a result of the inventions in the late 20th century.

Moreover, the second Industrial Revolution led to several developments that have not been rivaled by the so-called third Industrial Revolution. The former created the modern sanitary system, doing away with the smog-choked, garbage-strewn cities of the 1870s, where food lacked refrigeration and few houses had water connections. It not only created the modern suburbs, but it led to the formation of two new social classes, including a group of large-scale entrepreneurs, such as John D. Rockefeller and Henry Ford, who together with their corporate managers and other allies mostly replaced landowners and merchants as America's dominant class. The inventions of the late 20th century have not produced a new social class but merely added to the ranks of the existing capitalist one.

The other class made by the second Industrial Revolution—blue-collar laborers—emerged when management engineers in the early 20th century wrested control of the manufacturing process from skilled workers such as machinists. The approach, called "scientific management," altered profoundly the nature of work, because it helped to produce a class of workers who, in a sense, were involuntarily tied to their machines but were better paid.

Rodger Doyle can be reached at rodgerpdoyle@verizon.net



RODGER DOYLE; SOURCE: *HISTORICAL STATISTICS OF THE UNITED STATES, MILLENNIAL EDITION*. DATA FOR 1700–1790 ARE ESTIMATED; INVENTIONS ARE GROUPED BY YEAR OF ANNOUNCEMENT, NOT BY YEAR OF PRACTICAL APPLICATION

FURTHER READING

The Unbound Prometheus: Technological Change and Industrial Development in Western Europe from 1750 to the Present. David S. Landes. Cambridge University Press, 1969.

Was the Industrial Revolution Necessary? Edited by Graeme Donald Snooks. Routledge, 1994.

Does the "New Economy" Measure up to the Great Inventions of the Past? Robert J. Gordon. NBER Working Paper No. 7833, August 2000.

Historical Statistics of the United States, Millennial Edition. Edited by Susan B. Carter et al. Cambridge University Press, 2006. (Includes useful articles on the origin and reliability of the statistics.)

Bowling for God

Is religion good for society? Science's definitive answer: it depends

By MICHAEL SHERMER

Is religion a necessary component of social health? The data are conflicting. On the one hand, in a 2005 study published in the *Journal of Religion & Society*—"Cross-National Correlations of Quantifiable Societal Health with Popular Religiosity and Secularism in the Prosperous Democracies"—independent scholar Gregory S. Paul found an inverse correlation between religiosity (measured by belief in God, biblical literalism, and frequency of prayer and service attendance) and societal health (measured by rates of homicide, childhood mortality, life expectancy, sexually transmitted diseases, and teen abortions and pregnancies) in 18 developed democracies. "In general, higher rates of belief in and worship of a creator correlate with higher rates of homicide, juvenile and early adult mortality, STD [sexually transmitted disease] infection rates, teen pregnancy, and abortion in the prosperous democracies," Paul found. Indeed, the U.S. scores the highest in religiosity and the highest (by far) in homicides, STDs, abortions and teen pregnancies.

The secular left–religious right divide is distinct even if it isn't absolute.

On the other hand, Syracuse University professor Arthur C. Brooks argues in *Who Really Cares* (Basic Books, 2006) that when it comes to charitable giving and volunteering, numerous quantitative measures debunk the myth of "bleeding heart liberals" and "heartless conservatives." Conservatives donate 30 percent more money than liberals (even when controlled for income), give more blood and log more volunteer hours. In general, religious people are more than three times more generous than secularists to all charities, 14 percent more munificent to nonreligious charities and 57 percent more likely than a secularist to help a homeless person. In terms of societal health, charitable givers are 43 percent more likely to say they are "very happy" than nongivers and 25 percent more likely than nongivers to say their health is excellent or very good.

Are the left and right so religiously cleaved? According to Harvard University professor Pippa Norris and University of Michigan at Ann Arbor professor Ronald Inglehart in their book *Sacred and Secular* (Cambridge University Press, 2004), data from the Comparative Study of Electoral Systems analyzing 37 presidential and parliamentary elections in 32 nations over the past decade showed that 70 percent of the devout (attend religious services at least once a week) voted for parties of the right, compared with only 45 percent of the secular (never attend religious services). The effect is striking in America. In the 2000 U.S. presidential election, for example, "religion was by far the strongest predictor of who voted for Bush and who voted for Gore—dwarfing the explanatory power of social class, occupation, or region."

The theory of "social capital" may help resolve these disparate findings. As defined by Robert Putnam in his book *Bowling Alone* (Simon and Schuster, 2000), social capital means "connections among individuals—social networks and the norms of reciprocity and trustworthiness that arise from them." In their analysis of data from the World Values Survey, for example, Norris and Inglehart found a positive correlation between "religious participation" and membership in "nonreligious community associations," including women's, youth, peace, social welfare, human rights and environmental conservation groups (and, apparently, bowling leagues). "By providing community meeting places, linking neighbors together, and fostering altruism, in many (but not all) faiths, religious institutions seem to bolster the ties of belonging to civic life."

Religious social capital leads to charitable generosity and group membership but does comparatively worse than secular social capital for such ills as homicides, STDs, abortions and teen pregnancies. Three reasons suggest themselves: first, these problems have other causes entirely; second, secular social capital works better for such problems; third, these problems are related to what I call moral capital, or the connections within an individual between morality and behavior that are best fostered within families, the fundamental social unit in our evolutionary history that arose long before religions and governments. Thus, moral restraints on aggressive and sexual behavior are best reinforced by the family, be it secular or sacred. SA

Michael Shermer is publisher of Skeptic *(www.skeptic.com). His new book is* Why Darwin Matters.

BRAD HINES

Putting Up with Self

Critics warned of bad experiments and false hope. But Denise Faustman seems to be right about a strategy to regrow insulin-making cells killed off in diabetes By PHILIP E. ROSS

Five years ago Denise Faustman stunned the biomedical world—and not in a good way, it seemed. She declared that she had cured diabetic mice by getting them to regrow their insulin-producing beta cells, a finding that, if it could be translated to humans, would spare the million-odd Americans with type 1 diabetes their daily needle pricking and insulin dosing. Since her announcement, the academic establishment has given Faustman little money and a lot of flak. Researchers complained that they could not replicate the experiments and that the Harvard Medical School researcher had cruelly raised hopes that would only be dashed.

KATHLEEN DOOHER

DENISE FAUSTMAN: ISLET RESTORATION

- **Showed that the insulin-producing function of islet cells may be restored in type 1 diabetes. Later she presented data for true islet regrowth and suggested that transplanted spleen cells convert to functional islets.**
- **Type 1 diabetes results from an autoimmune attack on islet cells, as distinct from type 2 diabetes, in which the body becomes resistant to the effects of insulin.**

Faustman's vindication, however, finally seems to be at hand. In March three groups reported separately in *Science* that they had repeated Faustman's protocols and reproduced her most important result, stopping the disease process in about half their mice and getting the animals to recover normal function. "The results are fantastic, coming from these groups, which were each paid $1 million to spend three years showing that I was wrong," she remarks. "I mean, they were all funded by the JDRF."

The Juvenile Diabetes Research Foundation, the leading nonprofit source of research money in the field, had declined to back her work. The foundation states that it cannot fund all the research proposals it receives, but Faustman says that it had bowed to the tyranny of preconceived notions. Until recently, she says, it was taken for granted that once the beta cells are lost, they can never grow back. She had to go instead to a foundation set up by Lee Iacocca, the former chairman of Chrysler Corporation, whose wife died of diabetic complications. In total, Faustman has raised $11 million and is preparing preliminary human trials of an adaptation of her mouse therapy.

The 50-year-old Faustman says her work also undermines an important rationale for a favored subject of diabetes research, embryonic stem cells. The hope has been to get these stem cells to turn into beta cells and thereby furnish an ample supply of the scarce tissue. The JDRF and many diabetes activists support research on such stem cells, but the Bush administration has curtailed federal funding for it after coming under pressure from some conservative and religious groups.

Faustman got her idea by chance while transplanting islets, the pancreatic bodies that contain beta cells, from normal mice into others that had lost theirs to

type 1, or juvenile, diabetes. In this form, the immune system mistakenly attacks its own islets as if they were foreign invaders. Such autoimmunity—or inability to tolerate "self"—impairs the islets' function and eventually kills them. Patients must then inject insulin many times a day to control the fluctuating level of glucose in their blood.

To suppress the autoimmunity, Faustman injected mice with a cocktail of bacterial irritants called Freund's complete adjuvant, which made their bodies churn out a signaling chemical called TNF-alpha. This compound destroyed the activated immune cells, particularly those that targeted islets, so that when a surgeon implanted islets on the kidneys of each mouse, the transplants could take root, make insulin and restore normal blood sugar control.

That was when Faustman took a trip to the land of Serendip. "I wanted data for a figure showing how the blood sugar went up again after you take out the kidney with the islets in it," she recalls. The kidneys of two mice were removed, and "the day after the surgery, the mice were about 110 [milligrams of sugar per deciliter of blood—a normal reading], and both the animals were running around in the cage." In a 2001 paper she concluded that the mice had grown new islets.

Unfortunately, the cure was not permanent: the bad immune response returned. To eliminate the problem for good, Faustman borrowed an idea from the transplant specialists, who have found that liver or spleen cells can "reeducate" a graft recipient's immune system to treat the graft as native tissue. Here spleen cells from a nondiabetic mouse would teach a diabetic immune system how to be nondiabetic.

The ploy worked, and Faustman reported her results in *Science* in 2003. Her assertions provoked the criticism of a number of prominent researchers, including two Harvard colleagues, Diane Mathis and Christophe Benoist. They wrote to the *New York Times* criticizing an appreciative report the paper had run on Faustman, and although the paper declined to publish the letter, a version circulated in the diabetes community.

Yet William Ahearn, spokesman of the Juvenile Diabetes Research Foundation, says it was the 2003 paper that attracted the foundation's interest. The JDRF was "particularly excited" by what Faustman now describes as a secondary finding: the evident conversion of some spleen cells into beta cells. Spleen cells are easier to come by than beta cells, and if they could do the job, Ahearn says, the JDRF wanted them. That is why it funded the three groups to repeat Faustman's work.

Despite the positive results they announced in March, the three teams—from the University of Chicago, Washington University in St. Louis and the Joslin Diabetes Center (which included Mathis and Benoist)—nonetheless harbored doubts. They all sounded three sour notes: that they had cured only about half of their mice; that they did not know whether the mice had grown new islets or merely revived dormant ones; and that they had found no evidence that spleen cells had converted to beta cells.

But data announced this past June may allay those uncertainties. At the annual meeting of the American Diabetes Society in Washington, D.C., researchers from the medical schools of Keio and Osaka universities reported that they had substituted a tumor-derived islet for Faustman's spleen cells. Because these islets carried the kind of peptide that spleen cells use to reeducate the immune system, they were able both to control blood sugar and to end the autoimmune response. The proof came when the tumor-derived islets died off and the mice remained healthy. They must have grown beta cells of their own.

A second group, led by the National Institutes of Health, reported curing seven out of eight mice not only of diabetes but also of Sjögren's syndrome, an autoimmune disease that attacks the salivary glands. The investigators demonstrated robust new growth of islets and their saliva-making equivalents, and by a painstaking procedure, they proved Faustman's final proposition—that spleen cells had converted to both islets and salivary tissue. Éva Mezey of the NIH did the job by staining the same slice of tissue in two ways, once to pinpoint the secretion (either of insulin or of saliva) and a second time to pinpoint the male, or Y, chromosome. Because the donors of the spleen cells were male and the recipients female, any cell with the Y chromosome must have started out as spleen.

To eliminate diabetes in mice for good, Faustman borrowed an idea from transplant specialists.

Success in rodents, however, has so far not translated to humans. Researchers tried Faustman's therapy in patients with type 1 diabetes in Israel, using a TNF stimulant called BCG, which is much milder than Freund's complete adjuvant and has a long history of use in humans. The initially promising results failed to find confirmation in later trials in Canada and the U.S., a failure Faustman's critics have been quick to point out.

"But once we knew the mechanism," Faustman counters, "we went back and looked at the data and saw that the BCG dosage in Israel was 50-fold higher" than in the later trials. She says getting the correct dosage is all-important and plans to develop a biomarker to show whether the BCG is having even a subtherapeutic effect on the immune cells that target islets.

Faustman, who plans to test a version of her therapy herself in the clinic next fall, dismisses the criticism heaped on her work. "A lot of groups are working on this now," she says. "If imitation is the best form of flattery, then I'm flattered." SA

Philip E. Ross is Web editor of IEEE Spectrum *magazine.*

The Challenge of Sustainable Water

Water supplies around the world are already severely stressed. Population growth and global warming will only worsen those problems By JEFFREY D. SACHS

While oil shortages grab the headlines, water scarcity is creating at least as many headaches around the world. The most dramatic conditions are in Asia, where the world's two mega-countries, China and India, are grappling with deepening and unsolved water challenges. China's great northern plain, home to more than 200 million people, is generally subhumid or arid and depends on unsustainable pumping of underground aquifers for irrigation. The Yellow River has been diverted to the point that it no longer flows to the sea. Meanwhile the water tables of Beijing and other large northern cities are falling dramatically as a result of the pumping of groundwater.

Similarly, southern India is drought-prone, and southern states scramble after river flows that cross state boundaries. When the rains are poor, upstream states such as Karnataka turn off the water flow to downstream states such as Tamil Nadu, with brutal consequences for farmers and communities. In northern India, tens of millions of bore wells are depleting groundwater much faster than it can replenish, just as in China.

The Yellow River no longer flows to the sea.

Such problems are, of course, not limited to developing countries. Scarce river flows are bitterly contested among U.S. western states and between the U.S. and Mexico. A considerable portion of U.S. agriculture in the Great Plains depends on the vast but depleting Ogallala aquifer.

Continued population and economic growth will put still greater pressures on freshwater supplies. At this point, further claims on rivers and aquifers are often a zero-sum game: more water for one region means increased water scarcity and ecological destabilization elsewhere.

Climate change will raise the tension even further. Hundreds of millions of people in China, India and other parts of Asia depend on river flows fed by melting glaciers in the Himalayas. Those glaciers are receding and many will disappear this century, and the water supply will disappear along with them. Hundreds of millions of other people depend at least partly on snowmelt. Yet climate change will alter the timing of those flows even if the levels of snowfall remain the same. With warmer temperatures, the melting snows will fill the rivers earlier in the spring and will be unavailable for the long, dry summers.

Climate change will also alter the patterns of precipitation and evaporation in ways that are still poorly understood. Dry places are likely to get drier; rainfall is likely to arrive in fewer but more concentrated episodes; and extreme weather events such as tropical cyclones are likely to increase in intensity. My colleagues at the Earth Institute at Columbia University, for example, have used both theoretical reasoning and 1,000 years of tree-ring data to argue that global warming will likely intensify droughts in the American West. Some evidence, still heavily debated, suggests that warming surface temperatures in the Indian Ocean may be leading to droughts in parts of East Africa.

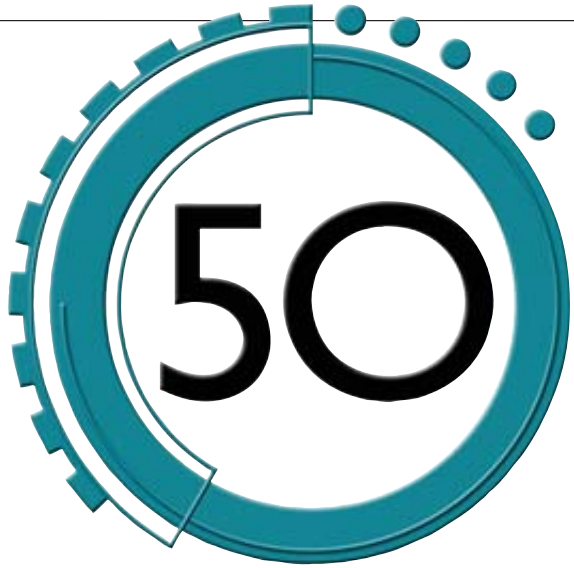
Solutions will not be simple. Yes, better pricing of water will lead to much greater efficiency. Drip irrigation can reduce the water demand of crops. Desalination can vastly expand water supplies, though at high energy costs. Water storage systems can spare farmers the misery of crop failures. But these solutions presuppose vast expenditures of capital, and such solutions do not automatically address the needs of the poor, who are unable to pay for that capital. Moreover, such solutions are often not commensurate with the scale of the challenge because they can bring huge adverse ecological consequences.

Securing water for a growing world will require the best of science, ecology, economics, ethics and international cooperation. With regard to climate change, the Intergovernmental Panel on Climate Change has done remarkable work in mobilizing the search for scientific consensus and possible solutions. A parallel effort on the science, technology and policy for water could prove to be of similar global benefit. SA

Jeffrey D. Sachs is director of the Earth Institute at Columbia University and of the U.N. Millennium Project.

An expanded version of this essay is available at www.sciam.com/ontheweb

BRUCE GILBERT/EARTH INSTITUTE



TRENDS

A group of scientists have detailed how to create materials that can redirect light around an object and make it invisible. This possible precursor to the ultimate camouflage demonstrates the depth of ingenuity of the 2006 Scientific American 50 awards.

These accomplishments go beyond invoking the Invisible Man. Drawn from the worlds of research, business and policymaking, a good number of the names on our list have in common an interest in leading technological innovation as a force for the public good: A fundamental understanding of the molecular processes that produce the mind-erasing devastation of Alzheimer's. A hybrid car that recharges by simply plugging into the wall. A billionaire who gives up much of his fortune to improve the state of global health.

Some of the inventions of this year's winners may soon be found at big retailers or in hospital dispensaries. Yet many of the researchers garnering accolades concentrated on basic questions, occupying themselves, for instance, with learning about the mechanisms that transform one stem cell type into a more specialized cell type—knowledge that will help answer the critical question of whether these wondrous biological entities will ever prove useful in clinical practice. Throughout the list of winners, that same theme reasserts itself: the most fundamental science precedes the technology that is eventually put to service in treating Alzheimer's or fashioning new devices that might outperform silicon electronics.

SA 50

RESEARCH LEADER OF THE YEAR

Angela Belcher

Massachusetts Institute of Technology

This eclectic investigator draws inspiration from nature's genius for building things at the nanoscale

Living things can serve as factories. Angela Belcher has used a virus to construct nanowires and semiconductor devices.

The crux of nanotechnology is the problem of self-assembly, getting uncooperative atoms to link and align themselves precisely. We know it can be done, of course: life persists by turning molecules into complex biological machinery. How fitting, then, that one of today's most creative materials scientists, Angela Belcher of the Massachusetts Institute of Technology, has turned to nature for assistance. Belcher has pioneered the use of custom-evolved viruses in synthesizing nanoscale wires and arrays, fusing different research disciplines into something uniquely her own.

Belcher's goal is to harness living things as factories for assembling materials made from any of the elements of the periodic table. Her greatest success has come from the M13 bacteriophage, a long, tubular virus six nanometers wide. She engineered a version of the virus that latched onto quantum dots, tiny specks of semiconductor with desirable electromagnetic properties. By suspending the virus particles, she could make them line up, an effective means of creating finely spaced layers of quantum dots that are separated by layers of virus.

More recently, she customized M13 to stud its length with metal particles such as cobalt oxide and gold, yielding metal nanowires that could be assembled into high energy-density electrodes. Those could be incorporated, for example, into lightweight, thin-film batteries that can be easily molded to fit any space. Belcher co-founded Cambrios Technologies in Mountain View, Calif., to turn some of these demonstrations into commercial devices such as flexible, touch-sensitive screens and light-emitting diodes. In her work, DNA shows its worth as more than just the code of life. —*JR Minkel*

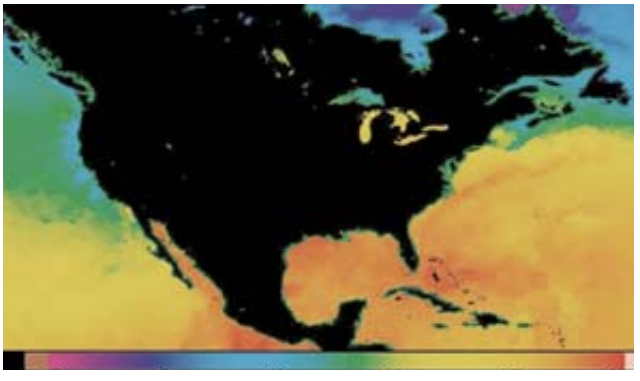
BUSINESS LEADER OF THE YEAR

SA 50

Swiss Re

Zurich, Switzerland

A top insurer highlights the dire consequences that could result from global warming



Global insurer Swiss Re has warned of the potentially disastrous effects of global warming, even co-sponsoring a report on its impact.

When one thinks of those trying to spread the word about the risks of global warming to society, one of the most reputedly staid industries probably does not leap to mind. Global reinsurer Swiss Re is looking to change that. Having long had its eye on climate change, the company co-sponsored a major report, released in late 2005, highlighting the potentially disastrous economic consequences of global warming. The report notes: "Insurers and reinsurers find themselves on the front lines of this challenge since the very viability of their industry rests on the proper appreciation of risk."

Climate change poses a special problem for the industry because it could dramatically change the rates of extreme weather events, perhaps to a point where insurers would be unable to keep up. The report, co-sponsored by the United

DONNA COVENEY *Massachusetts Institute of Technology* (*top*); NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (*bottom*)

Nations Development Program and published jointly with the Center for Health and the Global Environment at Harvard Medical School, outlines recent trends in climate and severe weather and traces the possible effects of two different climate change scenarios on prospects for heat waves and flooding, infectious and chronic disease, and managed and natural resources. Both scenarios are based on unchecked greenhouse gas emissions.

Swiss Re has a history of sensitivity to climate change concerns. In 2003 the insurer announced it was establishing a 10-year plan to become greenhouse "neutral," meaning it would reduce or offset the net carbon emissions of its employees to zero.

Last year the company joined the Chicago Climate Exchange, a voluntary market for greenhouse gas emissions trading. With the release of its 2005 report, Swiss Re called on governments and global industry to take much stronger action to mitigate the consequences of climate change: "[L]ittle action has been taken by most governments or businesses to address the potential costs of climate change. As all insurers know, however, risk does not compliantly bow to the political or business agenda." *—JR Minkel*

POLICY LEADER OF THE YEAR

SA 50

Al Gore

U.S. Vice President

The former presidential candidate is the preeminent spokesperson on climate change

It sounds improbable: a documentary film about global warming, starring Vice President Al Gore, has become the third-highest-grossing documentary of all time. After his loss in the 2000 presidential election, Gore began giving a talk on global warming to audiences around the world. *An Inconvenient Truth* is the film version (also appearing in book form) of his multimedia presentation. Remarkably, its heavy use of PowerPoint slides actually adds to the narrative, which interweaves explanations of climate science with defining episodes from Gore's life to convey a mix of alarm and hope.

The film is a paragon of clear science communication. It explains the workings of complex physical phenomena, such as the jet stream, while chronicling the reality of glaciers receding and the increase in carbon dioxide emissions and global temperatures. Gore, meanwhile, succeeds in bringing the "moral imperative" of reducing greenhouse gases to a personal level, attempting to convince viewers that their own actions can make a difference.

His appeal to individual responsibility is enhanced by the way the former politician, often lampooned for his stiff speaking style, gives the viewer a glimpse of his own life. In one of the film's strongest scenes, Gore recounts how his older sister's death from lung cancer led his family to stop growing tobacco—a painful metaphor for the industrial world's predicament in coming to grips with excess atmospheric carbon.

The film provoked commentary from across the political spectrum. After its release, the conservative Competitive Enterprise Institute attacked: "Carbon dioxide—they call it pollution; we call it life."

But movie critics drew attention to it by generally lavishing praise: "You owe it to yourself to see this film," urged Roger Ebert. "If you do not, and you have grandchildren, you should explain to them why you decided not to." The achievement of *An Inconvenient Truth* has been to bring the most important scientific and technical issue of our time into the public view better than anything before in print or film.

—JR Minkel and Gary Stix

Environmentalist Al Gore has dramatized the scientific case for global warming in the film *An Inconvenient Truth,* which has become one of the highest-grossing documentaries of all time.

More Than Government Grants

Entrepreneurial ingenuity focuses on finding money and ideas to advance medical science

To lift the burden of infectious diseases in poor nations, Harvard University economist **Michael Kremer** has advocated a kind of artificial market for vaccines. In Kremer's scheme, a donor would commit to paying a certain sum for the development of a vaccine and would purchase it at a high price per dose. After that, the company would supply the vaccine to poor countries at a low price.

Kremer's approach is one of many that have marshaled unprecedented creativity to chart new paths for medical research. A different attempt is the brainchild of **Scott Johnson**, a 50-year-old former businessman who is waging a personal battle against multiple sclerosis. His Myelin Repair Foundation, established in 2003, has persuaded five of the field's top university researchers to merge their laboratories and create a more businesslike plan for developing treatments.

Similarly, four leading cancer centers have linked efforts to coordinate clinical trials, share resources and pool their findings on a deadly bone disease: multiple myeloma, a blood cancer that erodes bones and often kills quickly. Leading the project is **Kathy Giusti**, a pharmaceutical executive who learned that she had multiple myeloma in 1996. A graduate of Harvard Business School, Giusti set up the Multiple Myeloma Research Foundation, which has raised $60 million for research.

Warren E. Buffett (*right*) is giving away 10 million shares (more than $30 billion) of his company, most of it to the foundation run by Bill and Melinda Gates (*left*).

Christiane Nüsslein-Volhard, a pioneering geneticist and co-winner of the 1995 Nobel Prize in Physiology or Medicine, has taken perhaps the most personal approach. With her own money and a $100,000 award from UNESCO-L'Oréal's Women in Science Program, she has launched a foundation in her own name that offers grants to young female scientists to pay for babysitters and household help.

Warren E. Buffett's innovation may be the most surprising of all. In what *Fortune* magazine described as "typical Buffett: rational, original, breaking the mold of how extremely rich people donate money," the world's second-richest man, after Bill Gates, is giving away 85 percent of his wealth, most of it to the Bill and Melinda Gates Foundation. The examples of Buffett and Bill and Melinda Gates are inspiring other leading executives and research professionals to bring their imaginations to bear on conducting the business of research.

—Michelle Press

On the Road to Green

Chemists and automakers mark progress toward environmentally benign fuels and vehicles

Motorists have heard a lot lately about ethanol-based fuels, which burn cleaner than gasoline and derive from renewable, domestic biomass. **Iogen Corporation** has furthered this technology by developing enzymes to convert tough, sugar-bearing cellulose in inexpensively produced agricultural waste into ethanol (*opposite page, top*).

Another renewable alternative fuel is biodiesel—predominantly vegetable oils that are processed to serve as a clean-burning fuel for diesel engines. **Michikazu Hara** of the Tokyo Institute of Technology and his colleagues have demonstrated that a charred mixture of inexpensive sugars, starches or cellulose can be treated to formulate an effective solid-acid cata-

SETH WENIG *AP Photo*

lyst for making biodiesel that is insoluble, cheap to prepare and easy to recycle.

Engineers are toiling to make diesels operate with fewer nitrogen oxide emissions. A leader in this quest is German-based automaker **DaimlerChrysler**, which recently introduced BLUETEC technology—a modular exhaust treatment system that cuts nitrogen oxide and soot output significantly, enabling cars to meet the most stringent U.S. emission standards.

Another technology that gets better mileage than standard engines, and hence produces less carbon dioxide for each mile driven, is the gasoline-electric hybrid, which marries a gasoline engine with electric motors. Current hybrid vehicles save fuel in stop-and-go driving but provide little mileage benefit on the highway. The new two-mode hybrid system from **General Motors**, **DaimlerChrysler** and **BMW** boosts fuel efficiency at both low and high speeds, improving combined mileage 25 percent over standard models.

Yet another way to raise the environmental performance of hybrid vehicles is to give them the means to store electrical grid power so that at times they can run on electricity alone instead of drawing power from a fossil-fuel-burning engine. These plug-in hybrids came closer to reality when two companies, **EDrive Systems**, a joint venture of EnergyCS and CleanTech in California, and **Hymotion**, a Canadian company, each introduced plug-in hybrid upgrade kits for the Toyota Prius. In the wake of these developments, the road to a greener, more sustainable energy future seems to be opening up.

—Steven Ashley

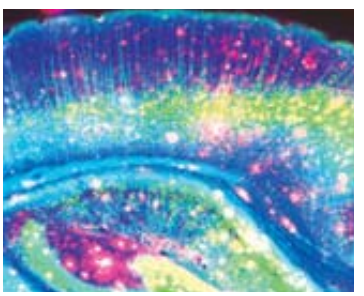
A top environmental official for the European Commission fuels a car with logen's cellulosic ethanol, derived from renewable biomass.

Unlocking Alzheimer's

Understanding the workings of a key protein may presage treatments

With the elderly segment of populations ballooning worldwide, the race to defeat that grim corollary of aging, Alzheimer's disease, is becoming all the more urgent. This year saw several encouraging advances on that front. In what reviewers described as a "technological tour de force," **John R. Cirrito** and **David M. Holtzman** of the Washington University School of Medicine in St. Louis traced production of a destructive Alzheimer's protein, known as amyloid-beta (*right*), to the junctions between neurons called synapses. They then directly linked high synaptic activity to amyloid-beta increases.

One key to counteracting the devastating effects experienced by patients is detecting the disease early, and another feat by Holtzman, with **Randall J. Bateman**, also at the Washington University School of Medicine, should make that possible. They have devised a test that measures the manufacture and disposal of amyloid-beta in the brain. Their technique might eventually serve as a basis for detecting the disease early and measuring drug effects on already diagnosed patients.



A mouse brain genetically engineered to exhibit the pathologies of Alzheimer's disease helps to define the destructive role played by amyloid-beta protein (*red*).

One of those treatments might someday be based on a synthetic protein fragment that **Robert P. Hammer** of Louisiana State University has developed to disrupt formation of the plaques believed to provoke massive brain cell death in Alzheimer's patients. The plaques are aggregations of fibers that form when individual amyloid-beta peptides begin sticking together abnormally. Hammer tweaked building blocks of amyloid-beta, synthesizing a nonsticky version of the amino acids that bind the proteins. Adding the engineered fragments to a test tube of normal amyloid-beta blocked the proteins' ability to form fibers, even after four months' exposure. If it does the same in human brains, tens of millions of Alzheimer's sufferers might finally be liberated from a deadly burden of poisonous plaque.

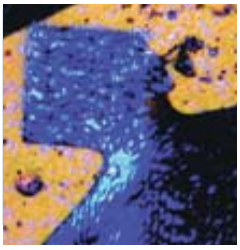
—Christine Soares

IOGEN CORPORATION (*top*); ROBERT P. BRENDZA AND JOHN R. CIRRITO, LABORATORY OF DAVID M. HOLTZMAN *Washington University School of Medicine in St. Louis* (*bottom*)

Beginning to See the Light

Two-dimensional light waves point toward optical imaging of viruses and the Invisible Man

In a remarkable feat of lateral thinking several years ago, electrical engineer **Igor I. Smolyaninov** deduced the properties of electromagnetic waves by applying the physics of time machines. The University of Maryland professor was studying what has become one of the sexiest areas of materials science: plasmonics, in which light is turned from a three-dimensional wave (a photon) into a two-dimensional one (a plasmon) rippling along, for example, the side of a metal sheet. If you put a droplet of liquid on the sheet, the plasmons can be trapped—just like photons inside a black hole. In fact, the hole might be used to create an analogue to a time machine and cause all the contradictions familiar to aficionados of science fiction. Smolyaninov reasoned that if time machines do not work, then neither should their analogues, from which he drew conclusions about the behavior of the waves.



Plasmon microscope captures nanometer-scale detail on a square chip.

He and his colleagues have now used the liquid-droplet black hole analogue to create a microscope that can see details smaller than the wavelength of the illuminating light—a feat that physics textbooks used to say was impossible. The key is that plasmons have a shorter wavelength than the photons from which they were converted, so they respond to finer features. Smolyaninov's team used laser light with a wavelength of about 500 nanometers to generate plasmons with a wavelength of 70 nanometers. A drop of glycerin focused them to form a 2-D image, which a regular optical microscope viewed (*above*).

Like plasmonics, the related science of metamaterials—the creation of artificial atoms with optical properties unlike those of any natural atom—is a door into a world so fantastic that it must surely be imaginary and yet isn't. This spring **John B. Pendry** of Imperial College London, along with **David Schurig** and **David Smith** of Duke University, and, independently, **Ulf Leonhardt** of the University of St. Andrews in Scotland predicted that a shell of metamaterials could redirect light around an object and render it invisible. The Duke researchers demonstrated an "invisibility cloak" in October.

Nader Engheta of the University of Pennsylvania and his colleagues have proposed a standardized set of plasmonic components akin to resistors, capacitors and inductors, which could let engineers build circuits using light rather than electricity. One day soon the fantastic world of plasmonics may be hanging from the rack at RadioShack.

—*George Musser*

The Promise of the Mother Cell

Stem cell biology continues to hint at medical benefits to come

A recent research trend has targeted the goal of having one's stem cells and preserving embryos, too—a nod to powerful critics such as President George W. Bush. Even if an embryo remains intact—the objective of these studies—it is unclear whether these methods will ever satisfy Bush and others who rail against what they perceive as immoral tinkering with the stuff of life.

Kevin Eggan and his colleagues at the Harvard Stem Cell Institute brought together embryonic stem cells with skin cells, or fibroblasts, creating fusion cells that reprogrammed themselves to resemble embryonic stem cells genetically matched to the donor of the skin cell. These cells would have the versatility to turn into any other cell type—and would not require a cloning procedure that necessitates the destruction of an embryo.

The promise of stem cells was again reaffirmed by an experimental therapy to treat patients with lupus—a disease in which the patient's immune system targets the body's own tissue. A group led by **Richard K. Burt** of the Northwestern University, Feinberg School of Medicine, removed stem cells from the patient's bone marrow. Drugs then wiped out the population of white blood cells before the stem cells were returned to the body, where they formed new white blood cells that were less likely to make damaging antibodies. In a study of 48 patients, half did not have the disease after a period of five years.

Determining how an embryonic stem cell differentiates into mature cells might eventually allow development of methods to reprogram an adult cell. Those techniques might let the mature cell return to its pluripotent state, in which it is capable of turning into different cell types. **Laurie A. Boyer** and **Richard A. Young** of the Whitehead Institute for Biomedical Research and their colleagues demonstrated how three proteins control this process.

IGOR I. SMOLYANINOV *University of Maryland*

Another research finding highlighted the importance of exploring the complexities of stem cell biology without having to satisfy the demand for immediate medical benefits. **Susan L. Lindquist** of the Whitehead Institute and her collaborators demonstrated that the prion protein, which causes mad cow disease when malformed, has a critical stem cell–related function in the body in its normal state. The protein appears to help nurture and maintain the body's supply of stem cells that produce blood cells.

Bush's decision to limit stem cell research to 78 existing cell lines has hindered the field. Today far fewer cell lines are viable than the original number permitted, and many of them are contaminated. Representative **Diana DeGette** of Colorado, a Democrat, and Representative **Mike Castle** of Delaware, a Republican, have been trying to loosen restrictions. They have succeeded in getting support from their colleagues in Congress but were ultimately stymied by Bush's veto—the first of his administration. A commitment is needed to continue basic research on stem cells unfettered by political considerations.

—Gary Stix

Smart Tags Get Smarter

The next generation of electronic tags promises to outperform RFIDs

The proliferation of radio-frequency identification (RFID) devices over the past decade has been nothing short of remarkable. But one of the most sweeping promises of the RFID revolution—that the devices will replace the ubiquitous bar code—has not yet come to pass because of their cost. So researchers have been striving to build RFIDs from a cheaper material: plastic.

In 2005 a group of engineers at **IMEC**, a company based in Leuven, Belgium, overcame a major hurdle by constructing a diode made of pentacene, an organic compound that has semiconducting properties. Prior to IMEC's breakthrough, organic devices were considered too slow to power RFID chips. The next step came early this year when a group led by **Eugenio Cantatore** of Philips Research Laboratories in Eindhoven, the Netherlands, announced that it had built a fully functional RFID tag made entirely of plastic electronics. Such a chip would be simpler to manufacture than a silicon-based tag because the design could be directly printed onto a plastic substrate. The elimination of complex assembly may pave the way for low-cost RFID tags incorporated into product packaging. And because RFID readers have a range of a few meters, supermarket clerks could speed the checkout process by scanning all the contents of a grocery cart at once.

Meanwhile engineers at **Hewlett-Packard Laboratories** have devised a miniature wireless chip that could eventually replace RFID tags in many applications. Called the Memory Spot (*below*), the chip can hold up to four megabits of flash memory and transfer those data to a reader at 10 megabits a second. It could be embedded into passports, postcards, pharmaceutical labels and hospital wristbands.

—Mark Alpert

Memory Spot embedded in a book could provide supplemental text, images and video to anyone with a portable reader.

COURTESY OF HP LABS

Chicken-Wire Electronics

Carbon structures provide new devices and remarkable physics

Since the 1985 discovery of buckyballs (such as the buckminsterfullerene—a nanoscopic sphere of 60 carbon atoms connected in a pattern similar to a traditional soccer ball), researchers have focused intense attention on various chicken-wire-like carbon structures. The latest addition to the menagerie is graphene, a flat single layer of carbon atoms bonded together in the hexagonal pattern of graphite.

In November 2005 two independent research groups, one led by **Andre K. Geim** of the University of Manchester in England and the other by **Philip Kim** of Columbia University, experimen-

tally confirmed some extraordinary electronic properties of graphene: the effective mass of electrons in graphene is zero, and they behave like elementary particles obeying a version of Einsteinian relativity instead of Newton's laws of motion. The results open up a remarkable new domain of relativistic physics that can be explored in tabletop experiments.

The development of graphene devices, which might eventually outperform silicon, took a major step forward when **Walter de Heer** of the Georgia Institute of Technology, along with his collaborators there and at the National Center for Scientific Research in France, used standard microelectronics-industry techniques to make graphene transistors and other circuitry. The ease with which graphene can be shaped to order could give it the edge over carbon nanotubes, which are much harder to build into complex devices.

Nanotube researchers are also continually breaking new ground. **Prabhakar R. Bandaru** of the University of California, San Diego, and his colleagues there and at Clemson University demonstrated a radically new kind of nanotube-based transistor. Its novel Y shape allows for the elimination of a metal electrode that controls current flow, enabling the transistor to be much smaller than previous designs.

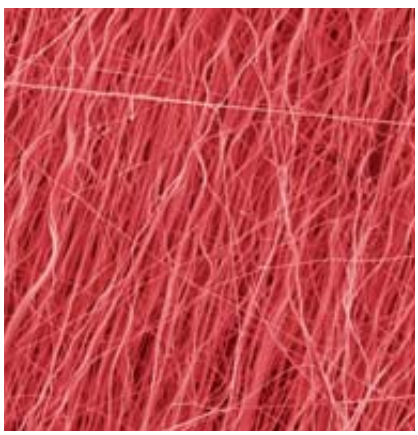
In the field of macroscopic materials made of carbon nanotubes, **Ray H. Baughman**, **Mei Zhang** and **Shaoli Fang** of the Nano-Tech Institute at the University of Texas at Dallas, along with their collaborators there and at the Commonwealth Scientific and Industrial Research Organization in Belmont, Australia, developed an efficient new way to make thin sheets of nanotubes that might be rapidly adaptable to commercial production. The sheets are strong, lightweight, transparent, highly flexible and electrically conductive, ideally suiting them to be used as components of displays, solar cells, organic light-emitting diodes and artificial muscles, among other applications. Whether it is flat as in graphene or rolled up into nanotubes, the chicken-wire form of carbon continues to go from strength to strength.

—Graham P. Collins

Growing Replacement Parts

Bioengineers can now cultivate blood vessels and other tissues from scratch

With the goal of mimicking the mechanical properties of soft tissue, bioengineers **William R. Wagner** and **Michael S. Sacks** of the University of Pittsburgh have fashioned an inexpensive polymer, polyester urethane urea, into a biodegradable scaffold. This cylindrical scaffold's strength resembles that of a pulmonary valve because it responds to stress differently depending on the direction in which the stress is applied. A patch of this biomaterial infused with smooth muscle cells (*right*) functions as vascular tissue, promoting healing and reducing formation of scar tissue in the hearts of rats recovering from cardiac arrest.



A polymer scaffold incorporates smooth muscle cells so that the device can serve as a foundation on which vascular tissue forms.

Already having reached the phase of clinical trials, the California bioengineering company **Cytograft** has patented a method for growing blood vessels from a human patient's own cells. In a feasibility trial undertaken in Argentina, Cytograft implanted its engineered vessels into two dialysis patients. Neither patient encountered problems with the implants for at least nine months.

One barrier to progress in tissue engineering results from the inability of thick tissue such as muscle, once implanted in a patient, to receive sufficient penetration of new blood vessels from the body's own network to keep the tissue alive. To address that problem, a multi-institution team spearheaded by **Shulamit Levenberg** of the Technion-Israel Institute of Technology in Haifa has created small pieces of muscle capable of generating its own blood vessels.

The researchers combined on a plastic biodegradable scaffold three types of cells: myoblasts that become muscle fibers, endothelial cells that form into vessel tubes, and fibroblasts that are the precursors to the smooth muscle cells that stabilize the cell walls. The endothelial cells became vessels, recruited fibroblasts and caused them to differentiate into smooth muscle cells. Once implanted in a rat, less than half the vessels became perfused with blood. But twice as many cells survived when implanted with the three cell types than implants made up of myoblasts and fibroblasts unaccompanied by the vessel-producing endothelial cells. The technique might eventually help address the persistent challenge of supplying engineered cells with oxygen and nutrients and allowing them to remove wastes.

—Brie Finegold and Gary Stix

WILLIAM R. WAGNER *University of Pittsburgh*

The two-legged robot called RABBIT walks in a manner similar to a human.

Robots on the Move

Improved mathematical models and sensors endow robots with enhanced mobility

In October 2005 teams watched their robots attempt to navigate the rugged Mojave Desert as part of a challenge sponsored by the Defense Advanced Research Projects Agency (DARPA). The previous year's challenge had ground to a halt when none of the competitors completed more than 5 percent of the 150-mile race. But last year everything changed. Four robots finished the race in fewer than 10 hours, and the winning **Stanford Racing Team**'s robot, fondly named Stanley, clocked speeds as high as 38 miles per hour. This dramatic turn of fortune can be attributed to advances in software and sensors.

While onboard laser and radar systems scanned the terrain, machine-learning algorithms tracked and studied the images, allowing Stanley, a modified Volkswagen Touareg, to swerve around obstacles and negotiate turns. Probabilistic methods for analyzing the road ahead kept Stanley from a common pitfall for robotic vehicles: hallucinating imaginary obstacles.

While Stanley may have a human name, the two-legged robot RABBIT has a disarmingly human gait (*left*). **Jessy W. Grizzle**, a control theorist at the University of Michigan at Ann Arbor, has tested his new mathematical model of walking and running on RABBIT, whose lower legs taper to wheels rather than feet. Because this robot is not able to statically balance on one leg, the model incorporates the effects of gravity more fully than other models. As scientists endeavor to automate more human tasks, robots may exhibit pleasing form as well as function.

—*Brie Finegold*

DNA Sequencing on the Cheap

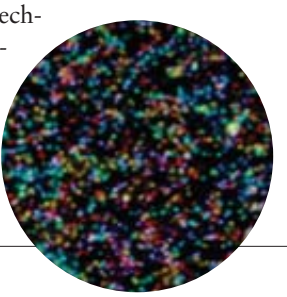
Optical technology advances toward the $1,000 genome

The exorbitant cost of deciphering a person's genome dropped sharply in 2005, from $20 million to roughly a tenth of that amount. DNA-sequencing technology using off-the-shelf equipment devised by **George M. Church** of Harvard Medical School and his collaborators both at Harvard and Washington University in St. Louis may help realize the federal goal of reducing that price to $1,000 by 2015, which experts say would make it practical to decode a person's genes for routine medical purposes. The build-it-yourself method (*right*) the Church group developed is based on combining widely available and relatively inexpensive microscopes with high-speed digital cameras.

A related technique from **454 Life Sciences** in Branford, Conn., also employs cameras coupled with microscopes to sequence DNA, except this method uses a different light-emitting technology than Church. Sequencing also usually relies on bacteria to multiply copies of the DNA target; both new methods instead use a combination of beads to grab the DNA and enzymes to reproduce it. The Church group's version works roughly 20 times faster than conventional sequencing, at a cost of $140,000. 454's system has a roughly 100 times higher throughput than conventional sequencing, at a cost of about $500,000 a machine.

In contrast to these optical technologies, current gene sequencing relies on electrophoresis, in which electric fields separate molecules based on their size and charge. **H. Kumar Wickramasinghe** of the IBM Almaden Research Center and his colleagues have devised a technique that combines electrophoresis with an atomic force microscope, which scans a surface by running extraordinarily sharp probes across it. The invention can sort DNA fragments roughly 100,000 times faster than conventional electrophoresis, albeit only with snippets up to 40 nucleotides long. The researchers note that their work could not only help accelerate DNA sequencing but also deliver molecules onto surfaces with unprecedented control.

—*Charles Q. Choi*



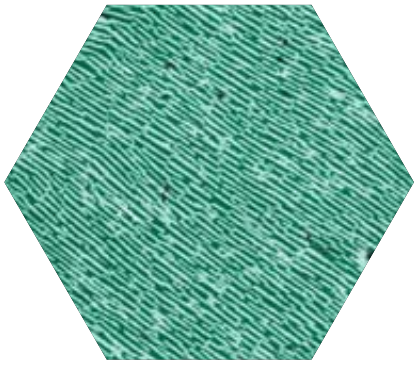
Researchers led by George M. Church of Harvard Medical School built low-cost sequencing technology that reads millions of fluorescing DNA beads at once.

CNRS (*top*); FROM JAY SHENDURE ET AL. IN *SCIENCE*, VOL. 309; SEPTEMBER 9, 2005; USED WITH PERMISSION BY AAAS (*bottom*)

Material Progress

Designers have crafted new structures ranging from nanorods to mimics of mother-of-pearl

Extraordinary properties emerge as scientists manipulate construction blocks at the nanometer scale. Diamond nanorods discovered by **Natalia Dubrovinskaia** of the University of Bayreuth in Germany and her colleagues pack together into a dense form of carbon that is harder than diamond. Potential industrial applications for materials made from nanorods include the cutting and polishing of alloys and ceramics.



A nacrelike ceramic material exhibits qualities of both strength and toughness.

Carbon was also the material chosen by **Pulickel M. Ajayan** and his colleagues at the Rensselaer Polytechnic Institute to create superresilient springs. The researchers used a foam made of carbon nanotubes to devise springs that combine the properties of stiffness and compressibility. Repeatedly compressing a cushion typically squashes it, making it lose its springiness. But the nanotube foams remained elastic even after 10,000 squeezes, a property that could make the material suitable for artificial joints or vibration dampeners.

Scientists draw inspiration from nature to come up with breakthrough materials. Modern ceramics are strong but brittle, whereas mollusk shells exhibit strength while retaining intrinsic toughness because of their finely layered mother-of-pearl, or nacre. **Antoni P. Tomsia** of Lawrence Berkeley National Laboratory and his colleagues found they could mimic nacre just by freezing a watery suspension loaded with hydroxyapatite, bone's mineral component (*left*). They built a multilayered nacrelike material that might find use in artificial bone and joints or in tissue regeneration.

Research that took inspiration from the natural world may also prove useful to the electronics industry, which often requires high temperatures and harsh acids or bases to produce thin films of silicon or other semiconductors. **Daniel E. Morse** of the University of California, Santa Barbara, found that by putting enzymes that mimic those of marine sponges onto gold surfaces, his team could create templates for growing semiconductor films. Inspiration from a lowly marine sponge may eventually yield more powerful batteries.

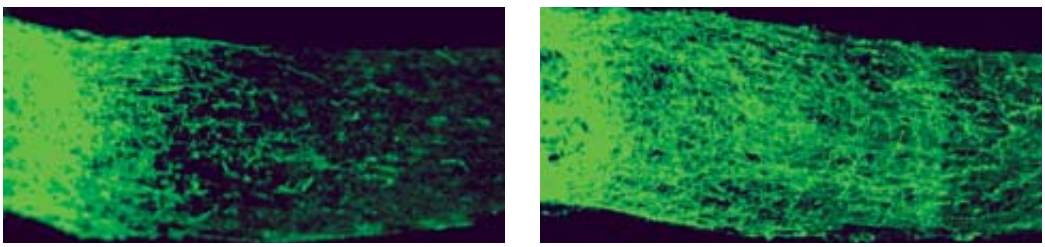
—*Charles Q. Choi*

Sight Savers

Technology that could help the blind see is now in the laboratory

Conventional wisdom specifies that the central nervous system—the brain, spinal cord and eye nerves—cannot heal in adults. This thinking no longer holds. **Larry I. Benowitz** of Children's Hospital Boston and his colleagues found a molecule that triggers better nerve regeneration than any other studied. The scientists discovered that a protein, oncomodulin, is secreted in damaged eyes by immune cells known as macrophages. They found that oncomodulin, when given with compounds that enhance its activity, can increase nerve regeneration fivefold to sevenfold in rats with injured optic nerves (*right*). Benowitz believes oncomodulin could someday help reverse optic nerve damage caused by glaucoma, tumors or trauma and plans to investigate whether the treatment could work to help treat stroke and spinal cord injury.

Another invention affords hope that some blind people may be able to view images and video. Visually challenged artist and poet **Elizabeth Goldring**, a senior fellow at the Massachusetts Institute of Technology's Center for Advanced



Regeneration of nerve fibers (*right panel*) occurs in the presence of a protein, called oncomodulin, secreted by immune cells.

FROM SYLVAIN DEVILLE ET AL. IN *SCIENCE*, VOL. 311; JANUARY 27, 2006; USED WITH PERMISSION BY AAAS (*top*); FROM YUQIN YIN ET AL. IN *NATURE NEUROSCIENCE*, VOL. 9, NO. 6; JUNE 2006 (*bottom*)

Visual Studies, developed just such a "seeing machine." It projects images directly onto the retina using light-emitting diodes, similar to much more costly scanning laser ophthalmoscopes used by medical institutions. In a pilot clinical trial of the seeing machine with 10 volunteers, most of whom were legally blind because of retinopathy and other causes, six correctly interpreted all 10 examples from a specially crafted visual language that combines words and pictures.

Prosthetics of another kind may in the future enable an amputee to use electrical signals from remaining muscles so that he or she can move an artificial arm more naturally. **Protagoras Cutchis** of Johns Hopkins University developed an electrode array implanted around the sheath of a peripheral nerve that does not penetrate into the nerve itself, unlike previous technologies. The electrode can process signals from electrical impulses from the brain that might eventually direct an arm to perform up to 22 distinct motions, far superior to previous prostheses that could move in only three directions. Machines are thus proving ever more able to take up the slack when the human body falters. —*Charles Q. Choi*

Of Brain Maps and Saving the Internet

An array of technologies are complemented by a push toward sensible public policy

The Ultimate Computer

Once a theoretical curiosity, the idea of a computer that stores information in quantum superpositions of 0 and 1, known as quantum bits or qubits, is edging slowly toward reality. This year researchers finally engineered microchips capable of rudimentary storage and manipulation of the quantum states of individual atoms, paving the way for convenient control over hundreds or thousands of atoms at once. **Christopher Monroe** of the University of Michigan at Ann Arbor (*below*) and **David J. Wineland** of the National Institute of Standards and Technology both fabricated chips capable of storing just a few charged atoms. —*JR Minkel*

Net Neutrality

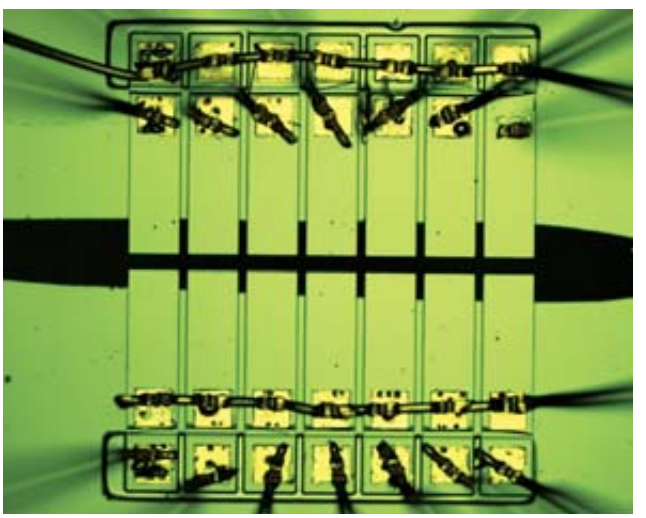
Phone and cable companies have recently begun floating the idea of charging major Internet content providers such as Google and Vonage for "premium" access to bandwidth. Outraged at the proposed tampering with so-called network neutrality—the concept that all Internet traffic should be carried and charged for in the same way—consumer groups lobbied the Federal Communications Commission to enshrine neutrality as a regulatory principle. Columbia University law professor **Timothy Wu** has been a leader in formulating and articulating the value of neutrality. —*JR Minkel*

DNA Building Blocks

One subdiscipline of nanotechnology devotes itself to building structures with molecules of DNA. Last year a team at the University of Oxford, working jointly with Vrije University in Amsterdam, described using DNA to construct a tetrahedron, a pyramid that has three faces and a base. The rigid structure measures 10 nanometers wide and could conceivably form a building block for electronic circuits that send currents along paths in three dimensions. The technique devised by Oxford's **Andrew J. Turberfield** allows the fabrication of trillions of these structures in just a few minutes. —*Gary Stix*

Brain Atlas

Three years ago Microsoft co-founder **Paul G. Allen** put up $100 million to establish the Allen Institute for Brain Science. Its first project would be the Allen Brain Atlas, aimed at accelerating efforts to map where and when every gene in the mouse brain is active. This September the institute unveiled the complete atlas, a three-dimensional map of 21,000 genes resolved down to individual cells. Because mice and humans share up to 90 percent of the same genes, researchers hope that such a map will provide insights into the genetics of human brain development, functioning and disease, including Alzheimer's, addiction and autism. —*JR Minkel*



A laser-based atom trap built at the University of Michigan at Ann Arbor may eventually enable the building of a quantum computer.

COURTESY OF CHRISTOPHER MONROE *University of Michigan at Ann Arbor*

SA 50

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Research Leader of the Year

1. Angela Belcher, Massachusetts Institute of Technology

Business Leader of the Year

2. Swiss Re

Policy Leader of the Year

3. Vice President Al Gore

Other Research, Business and Policy Leaders

More Than Government Grants

4. Michael Kremer, Harvard University (policy)
5. Scott Johnson, Myelin Repair Foundation (policy)
6. Kathy Giusti, Multiple Myeloma Research Foundation (policy)
7. Christiane Nüsslein-Volhard, Christiane Nüsslein-Volhard Foundation (policy)
8. Warren E. Buffett, investor/philanthropist (policy)

On the Road to Green

9. Iogen Corporation (business)
10. Michikazu Hara, Tokyo Institute of Technology (research)
11. DaimlerChrysler (business)
12. General Motors, DaimlerChrysler and BMW (business)
13. EDrive Systems and Hymotion (business)

Unlocking Alzheimer's

14. John R. Cirrito and David M. Holtzman, Washington University in St. Louis School of Medicine (research)
15. Randall J. Bateman and David M. Holtzman, Washington University in St. Louis School of Medicine (research)
16. Robert P. Hammer, Louisiana State University (research)

Beginning to See the Light

17. Igor I. Smolyaninov, University of Maryland (research)
18. John B. Pendry, Imperial College London, David Schurig and David Smith, Duke University, and Ulf Leonhardt, University of St. Andrews (research)
19. Nader Engheta, University of Pennsylvania (research)

The Promise of the Mother Cell

20. Kevin Eggan, Harvard Stem Cell Institute (research)
21. Richard K. Burt, Northwestern University, Feinberg School of Medicine (research)
22. Laurie A. Boyer and Richard A. Young, Whitehead Institute for Biomedical Research (research)
23. Susan L. Lindquist, Whitehead Institute for Biomedical Research (research)
24. Representative Diana DeGette of Colorado and Representative Mike Castle of Delaware (policy)

Smart Tags Get Smarter

25. IMEC (business)
26. Eugenio Cantatore, Philips Research Laboratories (business)
27. Hewlett-Packard Laboratories (business)

Chicken-Wire Electronics

28. Andre K. Geim, University of Manchester, and Philip Kim, Columbia University (research)
29. Walter de Heer, Georgia Institute of Technology (research)
30. Prabhakar R. Bandaru, University of California, San Diego (research)
31. Ray H. Baughman, Mei Zhang and Shaoli Fang, NanoTech Institute, University of Texas at Dallas (research)

Growing Replacement Parts

32. William R. Wagner and Michael S. Sacks, University of Pittsburgh (research)
33. Cytograft (business)
34. Shulamit Levenberg, Technion-Israel Institute of Technology

Robots on the Move

35. Stanford Racing Team (research)
36. Jessy W. Grizzle, University of Michigan at Ann Arbor (research)

DNA Sequencing on the Cheap

37. George M. Church, Harvard Medical School (research)
38. 454 Life Sciences (business)
39. H. Kumar Wickramasinghe, IBM Almaden Research Center (business)

Material Progress

40. Natalia Dubrovinskaia, University of Bayreuth (research)
41. Pulickel M. Ajayan, Rensselaer Polytechnic Institute (research)
42. Antoni P. Tomsia, Lawrence Berkeley National Laboratory (research)
43. Daniel E. Morse, University of California, Santa Barbara (research)

Sight Savers

44. Larry I. Benowitz, Children's Hospital Boston (research)
45. Elizabeth Goldring, Center for Advanced Visual Studies, Massachusetts Institute of Technology (research)
46. Protagoras Cutchis, Johns Hopkins University (research)

Of Brain Maps and Saving the Internet

47. Christopher Monroe, University of Michigan at Ann Arbor, and David J. Wineland, National Institute of Standards and Technology (research)
48. Timothy Wu, Columbia University (policy)
49. Andrew J. Turberfield, University of Oxford (research)
50. Paul G. Allen, Allen Institute for Brain Science (research)

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EDITORIAL CONTRIBUTORS

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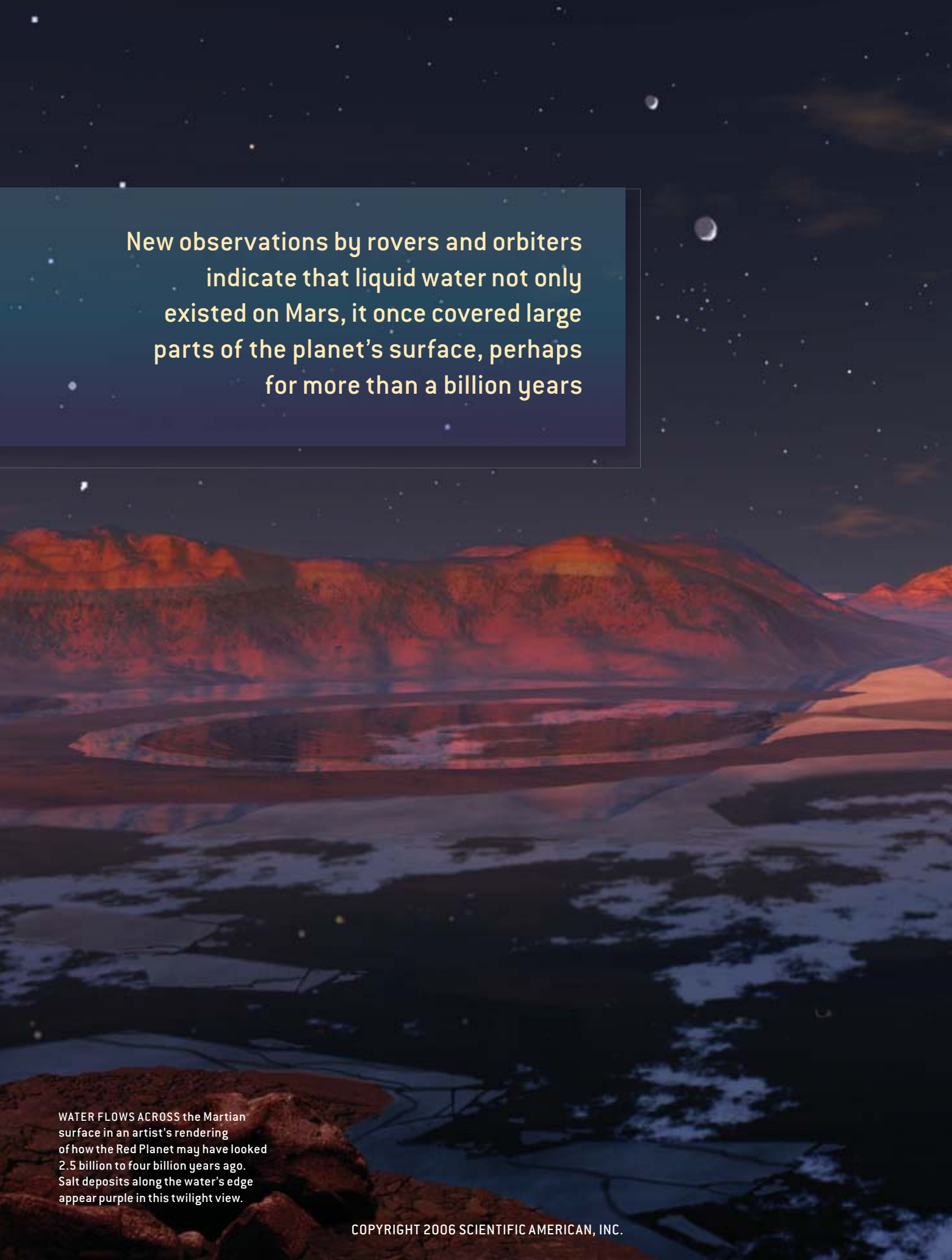
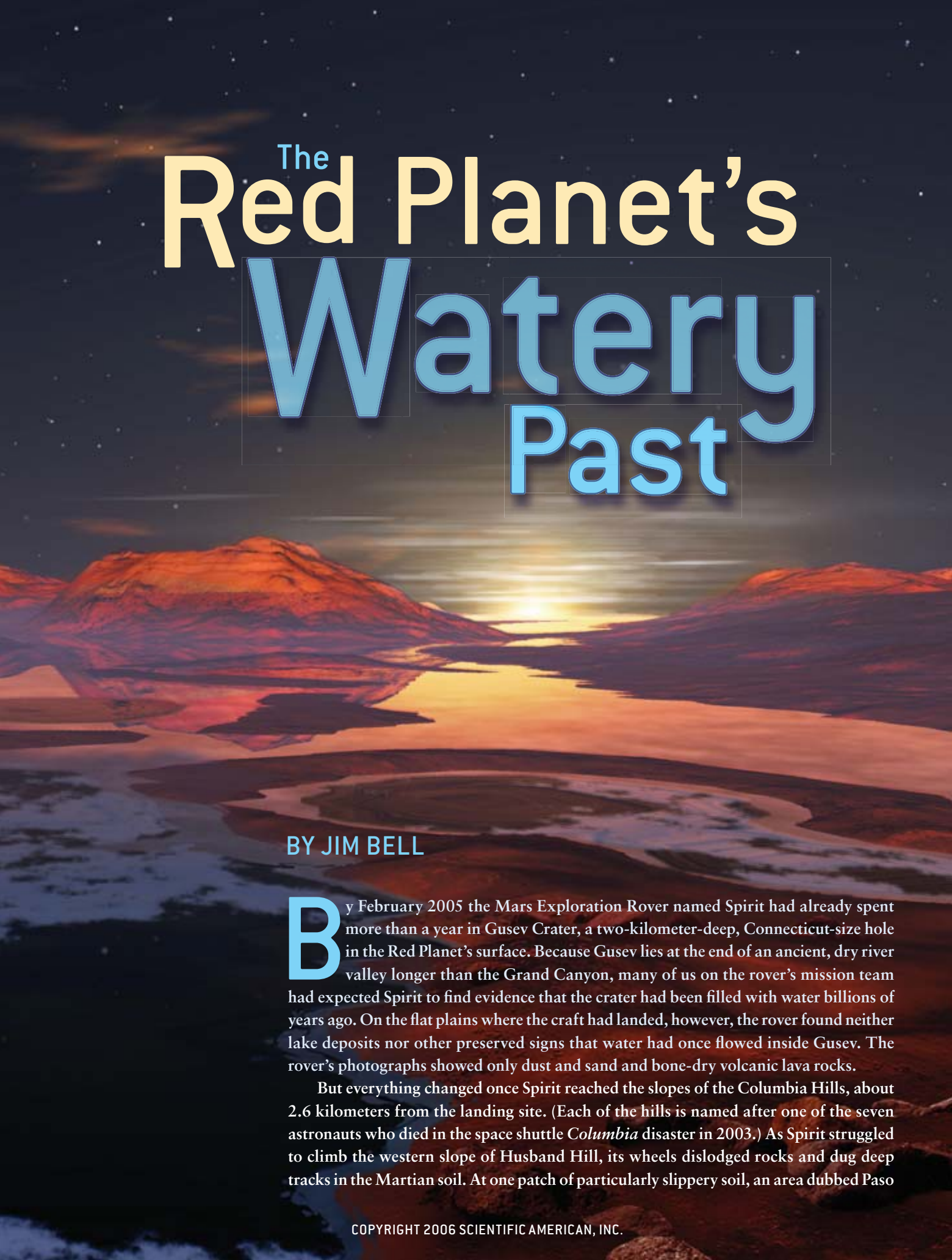


New observations by rovers and orbiters indicate that liquid water not only existed on Mars, it once covered large parts of the planet's surface, perhaps for more than a billion years

WATER FLOWS ACROSS the Martian surface in an artist's rendering of how the Red Planet may have looked 2.5 billion to four billion years ago. Salt deposits along the water's edge appear purple in this twilight view.



The Red Planet's Watery Past

BY JIM BELL

By February 2005 the Mars Exploration Rover named Spirit had already spent more than a year in Gusev Crater, a two-kilometer-deep, Connecticut-size hole in the Red Planet's surface. Because Gusev lies at the end of an ancient, dry river valley longer than the Grand Canyon, many of us on the rover's mission team had expected Spirit to find evidence that the crater had been filled with water billions of years ago. On the flat plains where the craft had landed, however, the rover found neither lake deposits nor other preserved signs that water had once flowed inside Gusev. The rover's photographs showed only dust and sand and bone-dry volcanic lava rocks.

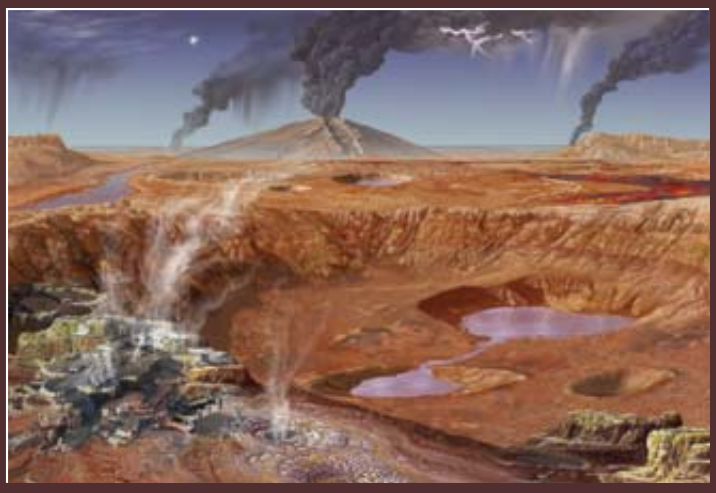
But everything changed once Spirit reached the slopes of the Columbia Hills, about 2.6 kilometers from the landing site. (Each of the hills is named after one of the seven astronauts who died in the space shuttle *Columbia* disaster in 2003.) As Spirit struggled to climb the western slope of Husband Hill, its wheels dislodged rocks and dug deep tracks in the Martian soil. At one patch of particularly slippery soil, an area dubbed Paso

Based on new evidence from recent missions to Mars, scientists have proposed a timeline positing an extensive watery past (dates are approximate).

4.6 billion to 4.2 billion years ago

ERA OF GIANT IMPACTS
After Mars's formation, asteroids and comets bombard the planet, forming huge impact basins and triggering intense volcanism. Oceans of magma (liquid rock) flow across the surface.

4.2 billion to 3.5 billion years ago



EPISODES OF EARTH-LIKE CONDITIONS
As the impacts lessen, liquid water fills some of the basins and carves enormous river valleys. The water weathers the underlying rock, producing clays and other hydrated silicates.

Robles, the wheels accidentally uncovered some exotic, whitish deposits that were unlike anything we had seen before in Gusev. Actually, Spirit had driven well past the Paso Robles soils before the mission team noticed them; when we saw what we had uncovered, though, we did the rover equivalent of slamming on the brakes and pulling a U-turn.

On further inspection, we determined that the deposits were hydrated sulfate minerals, rich in iron and magnesium, concentrated just below the dusty surface. On Earth these kinds of deposits are found in places where salty water has evaporated or where groundwater interacts with volcanic gases or fluids. Either process could have also taken place on Mars. (Although scientists have found no active volcanoes in Gusev or anywhere else on Mars, eruptions certainly occurred earlier in the planet's history.) Regardless of which hypothesis was right, we realized that these buried sulfate salts could be remnants of a past watery environment in Gusev.

Spirit's serendipitous find was consistent with discoveries made by Opportunity, the rover investigating the other side of Mars, and the small armada of satellites photographing the planet's surface from orbit. For decades, scientists had believed that Mars had always been a cold, dry, inhospitable world; the signs of occasional floods and certain water-altered minerals were thought to be anomalies, representing brief deviations occurring in the very distant past, soon after the formation of the Red Planet 4.6 billion years ago. But the new rover and orbital and meteorite studies paint a picture that is quite different from the one many had imagined even just a few years ago. Water apparently covered large parts of the Martian surface for long periods, certainly very early in the planet's history and perhaps also more recently. The implications are profound: if the eras of Earth-like conditions were frequent and long-lasting, the possibility that life evolved on Mars appears much more likely.

Overview/*Moist Mars*

- Recent results from Mars rovers and orbiters show that warm, wet conditions may have prevailed on the planet for long periods during its early history.
- If the eras of Earth-like conditions were frequent and long, life would have had a better chance of evolving.
- Future missions to Mars may test this hypothesis by measuring the ages of ancient landforms.

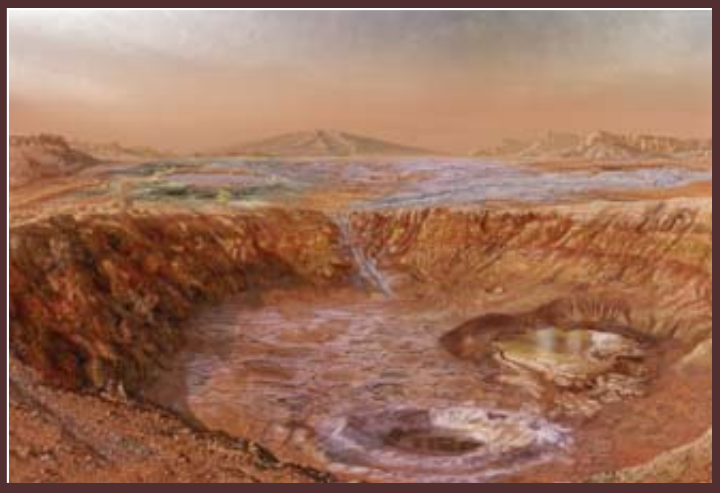
Flowing Landscapes

FLUVIAL LANDFORMS—geologic features putatively formed by water—were identified in images of Mars taken by the Mariner and Viking spacecraft in the 1970s. These landforms included enormous channels carved by catastrophic floods and large-scale valley networks somewhat reminiscent of river drainage systems on Earth. Over the past decade, images from the Mars Global Surveyor, which has been orbiting Mars since 1997, have revealed spectacular examples of extremely small and seemingly young gullies formed in the walls of some craters and canyons. These observations indicate the past presence of liquid water on the Martian surface or just below it but not necessarily for long periods. The water from the catastrophic floods, for example, may have lasted only a few days or weeks on the surface before freezing, seeping back into the ground or evaporating.

Furthermore, the networks of riverlike valleys shown in the Viking orbiter images do not have the same characteristics as

RON MILLER (*preceding pages*); MICHAEL CARROLL (*above and opposite page*)

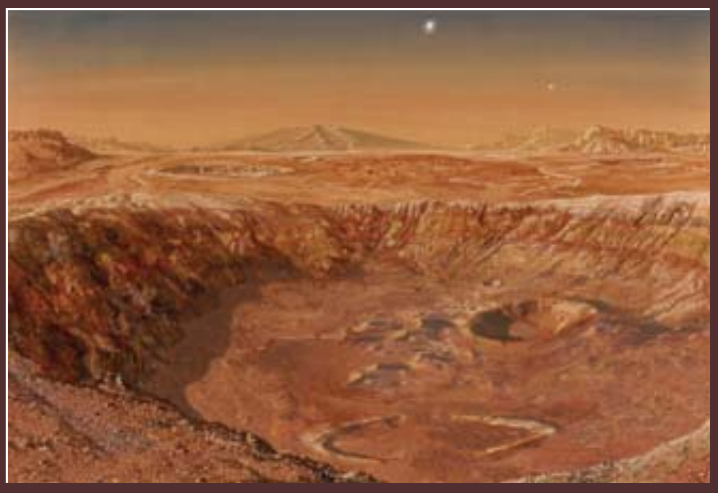
3.5 billion to 2.5 billion years ago



DRYING OUT AND COOLING DOWN

Sulfur from Mars's volcanoes dissolves in the pools of water, turning them acidic and destroying the clays. Surface water begins to freeze, but sporadic floods create large outflow channels.

2.5 billion years ago to present



ARID AND INHOSPITABLE

Volcanic activity wanes, and dust covers much of the planet. But liquid water may persist underground and occasionally burst to the surface, forming gullies in the walls of canyons and craters.

terrestrial river valleys when seen at higher resolution. The Martian valleys could have formed entirely from subsurface water flow and ground erosion—a process known as sapping—rather than from water moving over the surface. The gullies observed in the Mars Global Surveyor's images may also be the result of water seeping underground below ice or from buried snow deposits. Although these features are stunning and dramatic indicators of water on Mars, they do not firmly prove that the Red Planet once had a warmer, wetter, more Earth-like environment with long-lasting lakes and rivers.

In the past few years, however, new satellite images have provided much more compelling evidence that stable, Earth-like conditions prevailed on Mars for long periods. One of the most exciting discoveries is a class of features that look like river deltas. The best and largest example, photographed by the Mars Global Surveyor, is at the end of a valley network that drains into Eberswalde Crater in a region southeast of the Valles Marineris canyon system [*see illustration on page 68*]. This drainage system terminates in a 10-kilometer-wide, layered, fan-shaped landform characterized by meandering ridges that crosscut one another and show varying degrees of erosion. To many geologists, this feature has all the characteristics of a delta that formed at the end of a sediment-bearing river flowing into a shallow lake.

Like the Mississippi River delta, the structure of the Eberswalde fan suggests that it grew and altered its shape many times, most likely responding to changes in the flow of its ancient source river. If the Eberswalde fan actually is an ancient river-delta deposit, buried by later sediments and exhumed by more recent erosion, the implication is that liquid water persistently flowed across the Martian surface, eroding large volumes of sedimentary materials and transporting them downstream. Orbital images have revealed a handful of similar fans in other regions of Mars, but only 5 percent of the planet's surface has been photographed at the resolution needed to identify these features. Further orbital studies may allow researchers to test the river-delta hypothesis, but to determine how long the water flowed to create the fans, scientists will need to measure accurately the absolute or relative ages of different parts of the landforms. Determining absolute ages cannot be done from orbit; instead rock samples from these areas must be sent to Earth for detailed analysis or examined by future rovers that can perform radioisotope dating.

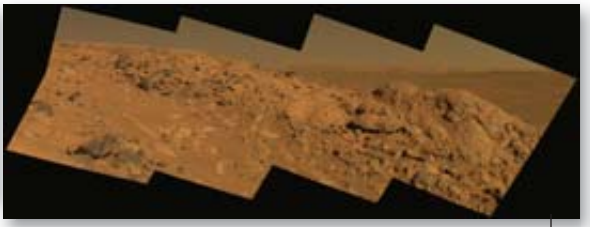
Additional evidence of an Earth-like climate in Mars's past comes from high-resolution images, taken by the Mars Odyssey and Global Surveyor orbiters, of the small-scale valley networks on the plateaus and walls of the Valles Marineris canyon system. Unlike previously identified valley networks that seem to have formed largely from subsurface flow, these newly found networks have characteristics that are consistent with their formation by rainfall or snowmelt and surface runoff. For example, the networks are arranged in dense, branching patterns, and the lengths and widths of the valleys increase from their sources to their mouths. Moreover, the sources are located along the ridge crests, suggesting that the landscape was molded by precipitation and runoff. Indeed, these landforms provide the best evidence to date that it may have rained on Mars.

A more speculative possibility is that these runoff features arose relatively recently, perhaps one billion to 1.5 billion years after Mars formed. To estimate the ages of Martian landforms, researchers count the number of impact craters on the feature—the more impacts the region has endured, the older it is. This dating method, however, has many uncertainties; it can be difficult to distinguish between primary and

SNAPSHOTS FROM THE HUNT FOR WATER

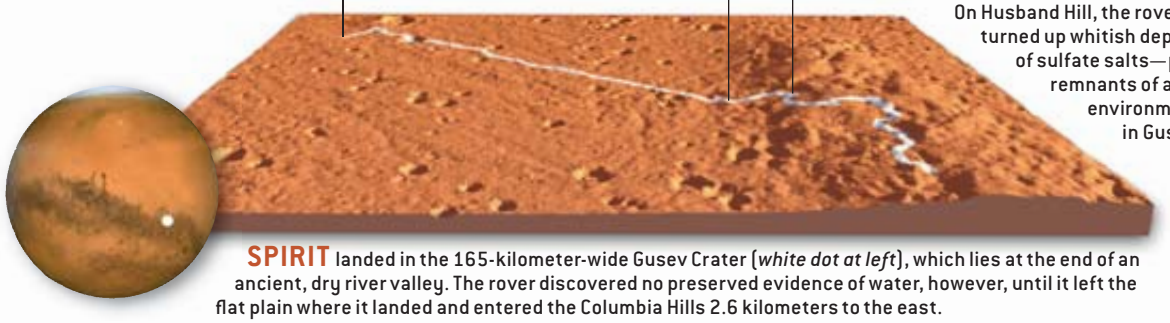
Spirit and Opportunity, the Mars Exploration Rovers that have been operating on the Red Planet since January 2004, have revealed some of the best evidence of a warm, wet past.

VIEW FROM LANDING SITE
Spirit found nothing but dust, sand and volcanic rocks at its landing site, but the Columbia Hills loomed in the distance.



LONGHORN AT WEST SPUR
Seven months into its mission, the rover reached the Longhorn outcrop in the West Spur region of the Columbia Hills.

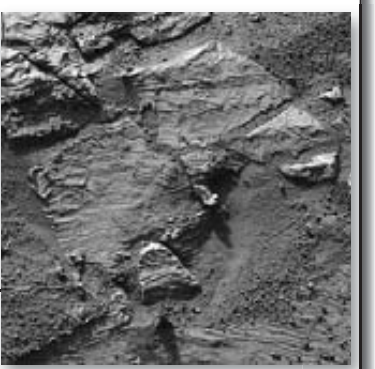
PASO ROBLES SOIL
On Husband Hill, the rover's wheels turned up whitish deposits of sulfate salts—possible remnants of a watery environment in Gusev.



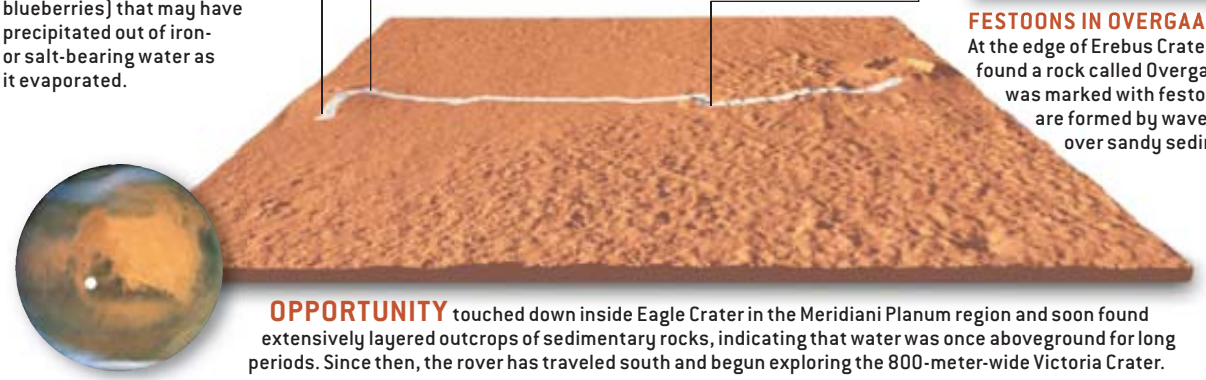
SPIRIT landed in the 165-kilometer-wide Gusev Crater (*white dot at left*), which lies at the end of an ancient, dry river valley. The rover discovered no preserved evidence of water, however, until it left the flat plain where it landed and entered the Columbia Hills 2.6 kilometers to the east.

BERRY BOWL
In Eagle Crater's outcrops, Opportunity found millimeter-size spherical grains (nicknamed blueberries) that may have precipitated out of iron- or salt-bearing water as it evaporated.

BURNS CLIFF
In nearby Endurance Crater the rover studied Burns Cliff, a massive layered outcrop that bolstered the hypothesis that water periodically covered the landscape.



FESTOONS IN OVERGAARD
At the edge of Erebus Crater the rover found a rock called Overgaard that was marked with festoons, which are formed by waves washing over sandy sediments.



OPPORTUNITY touched down inside Eagle Crater in the Meridiani Planum region and soon found extensively layered outcrops of sedimentary rocks, indicating that water was once aboveground for long periods. Since then, the rover has traveled south and begun exploring the 800-meter-wide Victoria Crater.

NASA/STScI/JIM BELL (*global images*); RON MILLER (*traverse maps*); NASA/JPL/CORNELL (*landing site, Longhorn, Paso Robles*); NASA/JPL/CORNELL (*Berry Bowl, Burns Cliff*); NASA/JPL-CALTECH/CORNELL (*festoons*)

secondary impact craters and volcanic calderas, and erosion has destroyed the evidence of craters in some regions. Still, if these surface runoff valleys do turn out to be relatively young, Mars may have had an Earth-like climate for as much as a third of the planet's history and perhaps longer if even younger valleys are eventually identified.

Yet another piece of evidence supporting persistent liquid water on Mars is the observation of truly enormous amounts of erosion and sedimentation in many parts of the planet. Making calculations based on new orbital imaging data, researchers have determined that the rate at which sediments were deposited and eroded in the first billion years of the planet's history may have been about a million times as high as the present-day rate. (Wind erosion rates have been estimated at the landing sites of the Spirit, Opportunity and Mars Pathfinder rovers.) For instance, the extensively gouged and pockmarked appearance of the region known as Meridiani Planum—the one-million-square-kilometer area in which Opportunity is operating—indicates that much of the terrain has been stripped by erosion and transported elsewhere. No one knows where all this eroded sediment ended up—that is one of the major unsolved mysteries in Mars research—but what does seem clear is that wind alone could not have excavated so much material.

In other places, such as the floors of some craters and the floors and walls of some canyons and chasms in Valles Marineris, cycles of deposition and erosion have apparently created tremendous stacks consisting of hundreds of layers of rock, each between 10 and 100 meters thick. One of the most remarkable examples sits inside the 170-kilometer-wide Gale Crater, which has a gigantic central mound of layered, eroded sedimentary rocks on its floor. The layers, channels and partially buried impact craters in the mound indicate a long and complex history of erosion and deposition. The most incredible characteristic of the mound, though, is that it rises to a height of nearly a kilometer above the rim of Gale Crater. It seems as if the crater and surrounding regions were completely buried by an enormous quantity of sediment, then partially exhumed and buried again, perhaps many times over a long period. The sediments have been eroding since the last burial event, exposing the crater's floor, but the central mound may be wearing down at a slower pace, explaining why it now stands higher than the crater's rim.

But what process could have transported the massive amount of sediment needed to bury almost everything in the Gale Crater region? Scientists believe flowing water offers the best explanation. Studies of erosion and sedimentation rates on Earth suggest that wind could have moved some of the Martian sediment in the past (just as it is doing today, albeit at a very slow pace). No viable wind-based scenario, however, can explain the rapid transport of millions of cubic kilometers of material across large fractions of the planet's surface, which apparently occurred repeatedly during Mars's early history. Flowing water, though, has routinely moved gargantuan amounts of sediment on Earth and could have done so on the Red Planet as well.

Clays, Berries and Waves

IN ADDITION TO scrutinizing the shape of Martian landforms, scientists have searched for hints of liquid water in the composition of the planet's minerals. One of the reasons why researchers had long believed that Mars never enjoyed an extensive period of warm and wet climate is that much of the surface not covered by wind-borne dust appears to be composed of material that is largely unweathered—pristine volcanic minerals such as olivine and pyroxene. If water had flowed over the surface for a long time, the argument went, it would have chemically altered and weathered the volcanic minerals, creating clays or other oxidized, hydrated phases (minerals that incorporate water molecules or hydroxide ions in their crystal structure).

Mars may have had an EARTH-LIKE CLIMATE for as much as a third of the planet's history.

It turns out, though, that the scientists were not looking closely enough. New high-resolution orbital mapping data and close-up surface studies from the Mars rovers have revealed abundant deposits of clays and other hydrated minerals in many regions. For example, the OMEGA instrument on the European Space Agency's Mars Express orbiter—which is particularly good at detecting the kinds of minerals that form from the weathering of volcanic rocks—has found clays in the dust-free parts of what appear to be the oldest terrains on the surface. Based on the high number of impact craters in these areas, their ages span much or all of the first billion years of Martian history. The clay deposits are scattered all over the planet, in ancient volcanic surfaces and heavily cratered highland regions, some of which have apparently been exposed by erosion only recently.

The newly discovered clays are phyllosilicates—minerals composed of sheets of silica with water molecules and hydroxide ions trapped between the sheets. The clays have the diverse range of compositions that one would expect from the water-

THE AUTHOR

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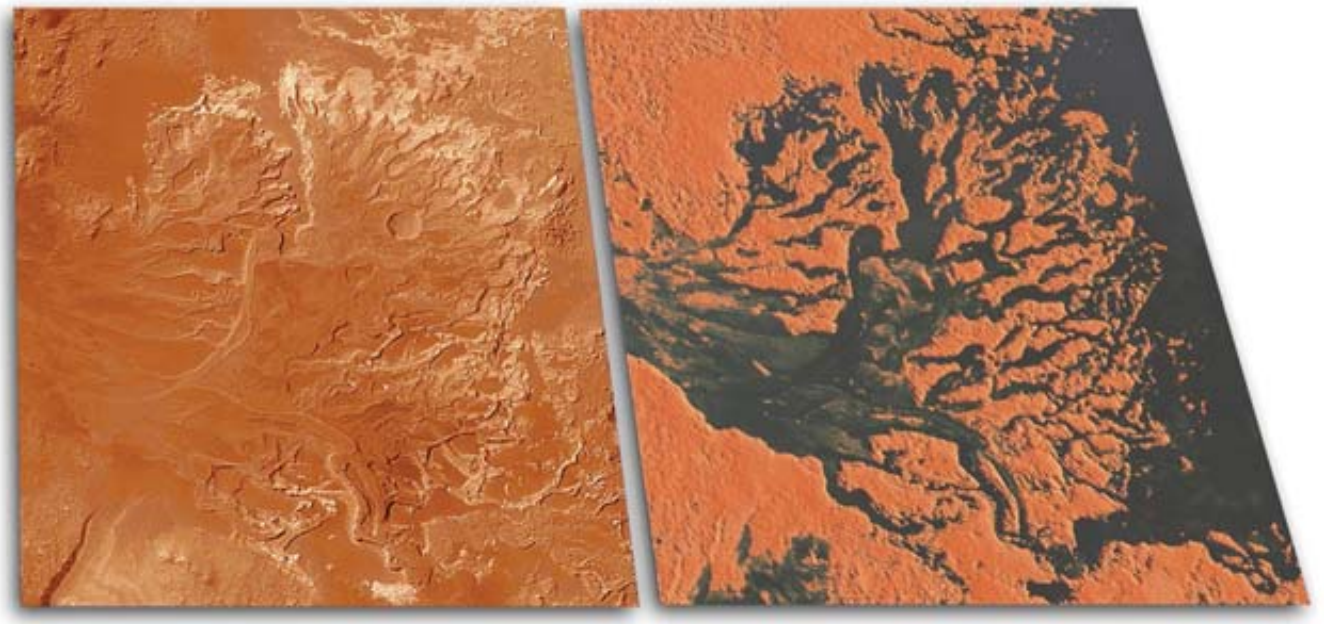


EBERSWALDE FAN (*left*), photographed from orbit by the Mars Global Surveyor, lies at the end of a valley network leading into Eberswalde Crater. The meandering, overlapping channels in the 10-kilometer-wide fan suggest that it was once a river delta draining into a shallow lake that may have filled much of the crater. The artist's rendering (*right*) portrays this delta as it might have looked billions of years ago.

related weathering of the various kinds of volcanic rocks that have been found on Mars. Although OMEGA has surveyed only a small fraction of the planet at high resolution so far, the discovery of these minerals is strong evidence of a long epoch of Earth-like conditions on early Mars.

Furthermore, researchers have detected minerals altered by water (clays, hydrated iron oxides and carbonates) in some Martian meteorites—rocks that were ejected from the Red Planet by comet or asteroid collisions and eventually landed on Earth. Scientists have hypothesized that the water-related weathering may have taken place underground, because most of the meteorites were part of the Martian crust, but not the uppermost surface, before they were blasted into space. And because some of the meteorites are thought to come from relatively younger parts of the Martian crust, investigators suspect that the subsurface weathering may be continuing today. Scientists may be able to test this important hypothesis in ongoing and future missions to Mars, perhaps by searching for evidence of active springs or hydrothermal activity. What is more, new landers, rovers or human missions could be equipped with drills for exploring deep underground.

The exploits of the Mars rovers have added the newest pieces to the Red Planet's climate puzzle. Eight months before the Paso Robles discovery, as Spirit was just beginning its climb into the Columbia Hills, the rover examined a knobby rock with its mineral-identifying instruments and detected hematite, a highly oxidized iron mineral that is common in soils on Earth that have been altered by water. Several months afterward, Spirit found evidence of phyllosilicates and goethite, an oxidized iron mineral that cannot form without water and that preserves water-derived hydroxide ions in its crystal structure. The Columbia Hills appear to record an ancient history of water-rock interactions on Mars that was not apparent in the younger volcanic plains that Spirit investigated earlier in its mission.

As the rover crested the summit of Husband Hill and eventually made its way down the other side and into the basin to the south, it encountered even more Paso Robles–like subsurface salt deposits. Unfortunately, we could not adequately study the most extensive deposits, because as the seasons advanced into the rover's second Martian winter, we were forced to move Spirit onto north-facing slopes so that there would be enough sunlight on the rover's solar panels to keep the machine operating. If all goes well, we will send the rover back to the salt deposits once the Martian spring returns.

Meanwhile Opportunity has made equally amazing finds in Meridiani Planum. Within weeks of landing, the rover had discovered ancient deposits of extensively layered, sedimentary outcrop rocks that were porous, hydrated and salty. From complementary orbital observations, researchers knew that these deposits spanned the entire region. The layered outcrops studied by Opportunity showed that these kinds of sedimentary rocks extend tens of meters deep (or more) into the subsurface, indicating that liquid water was once aboveground for long periods. Opportunity's results, however, portray a different part of the history of water on Mars. The hydrated rocks found by the rover contain predominantly sulfur-rich minerals such as jarosite, and the sedimentary outcrop rocks are rich in chlorine and bromine as well as sulfur. All these elements are highly mobile in watery solutions, implying that the deposits formed after the evaporation of salty liquid water. Thus, the outcrops may bear witness to a time when the pools and streams of Meridiani Planum gradually shrank and dried up.

The rover's discovery of millimeter-size, hematite-bearing spherical grains—nicknamed blueberries—in the outcrops

NASA/JPL/MALIN SPACE SYSTEMS, INC. (*orbital image*); RON MILLER (*rendering*)

also bolstered the hypothesis of long-term standing water on Mars. We believe that the blueberries are what geologists call concretions, grains that precipitate out of iron- or salt-bearing water as it evaporates. If the process is slow and homogeneous enough, the resulting mineral grains grow spherically. On Earth, some concretions grow to the size of marbles or ping-pong balls; the ones seen on Mars are the size of ball bearings, two to three millimeters across on average. As Opportunity moved south from its landing site, the blueberries it found were smaller, suggesting possible variations in the duration of the watery environment or the rate of the water's evaporation.

Opportunity has even photographed some outcrop rocks that appear to preserve the tracks of waves in shallow water. The best examples of these "festooned cross-bed sets," which are formed by waves interacting with sandy sediments, were found earlier this year as the rover traveled south across the plains.

The Emerging Paradigm

THE RESULTS FROM the rovers underline the importance of sulfur, which presumably built up in the Martian environment because of the planet's early and active volcanic history. Sulfur and sulfur-bearing minerals can dissolve in water, and the resulting solutions can be quite acidic. Acidic water destroys many kinds of minerals, particularly carbonates, and it also inhibits the formation of other minerals such as clays. Thus, the buildup of sulfur on Mars may explain why scientists have not yet found any carbonates on the surface and why clays appear to be preserved in only the oldest terrains. The OMEGA instrument has detected sulfate deposits at other locations on Mars besides Meridiani Planum, but in general these regions appear to be younger than the areas with clays. So far sulfates and clays have not been found together.

The emerging paradigm is that Mars had an extensive watery past: puddles or ponds or lakes or seas (or all of them) existing for long periods and exposed to what must have been a thicker, warmer atmosphere. During the first billion or so years of Martian history, the Red Planet was a much more Earth-like place, probably hospitable to the formation and evolution of life as we know it. The Martian environment began to change, however, as sulfur built up, the waters became acidic and the planet's geologic activity waned. Clays gave way to sulfates as the acid rain (of sorts) continued to alter the volcanic rocks and break down any carbonates that may have formed earlier. Over time, the atmosphere thinned out; perhaps it was lost to space when the planet's magnetic field shut off, or maybe it was blown off by catastrophic impacts or sequestered somehow in the crust. Mars eventually became the cold, arid planet we recognize today. This sequence of events would explain why any volcanic rocks that have erupted onto the surface in the past few billion years should still be unweathered and pristine. It is the older stuff underneath, serendipitously exposed by impacts or erosion or slip-sliding rovers, that holds the key to the planet's past.

This new view of Mars is not yet universally accepted, however. Key questions remain unanswered: How long did the waters flow in the Eberswalde delta—for decades or millennia? Where are all the sediments that appear to have been eroded from Meridiani Planum and places such as Gale Crater? And were they eroded by water or wind or something else? What is the global abundance of clay minerals on Mars, and were they ever major components of the planet's crust? And, most vexing, where are the carbonates that should have formed in the warm, wet, carbon dioxide–rich environment but have not yet been observed anywhere on Mars, not even in the older terrains where clays have been detected? Acidic water could have destroyed the bulk of the carbonates but surely not all of them!

The Martian environment began to change as the WATERS BECAME ACIDIC and geologic activity waned.

Perhaps the most important question of all is, Did life ever form on early Mars, and if so, was it able to evolve as the environment changed so dramatically to the present-day climate? The answer depends in large part on how long the Earth-like conditions lasted. None of the images or other data that we have in hand, as impressive as they are, can provide us with very good constraints on the duration of the warm, wet era. We simply do not understand the ages of Martian surfaces well enough. In fact, it may ultimately prove impossible to use the density of impact craters to establish absolute or even relative ages on a surface that has seen so many episodes of massive burial and erosion. A better method would be bringing Martian samples back to Earth for accurate radioisotope dating or sending miniature age-dating instruments on missions to the surface. Until then, orbital spacecraft will continue to hunt for key mineral deposits and identify the best sites for future landers and rovers, which may someday reveal indisputable estimates of the duration of the Red Planet's watery era. The past decade of discoveries on Mars may be only a small taste of an even more exciting century of robotic and eventually human exploration. SA

MORE TO EXPLORE

Evidence for Persistent Flow and Aqueous Sedimentation on Early Mars. M. C. Malin and K. S. Edgett in *Science,* Vol. 302, pages 1931–1934; December 12, 2003.

Evidence for Precipitation on Mars from Dendritic Valleys in the Valles Marineris Area. N. Mangold et al. in *Science,* Vol. 305, pages 78–81; July 2, 2004.

New Perspectives on Ancient Mars. S. C. Solomon et al. in *Science,* Vol. 307, pages 1214–1220; February 25, 2005.

Global Mineralogical and Aqueous Mars History Derived from OMEGA/Mars Express Data. J.-P. Bibring et al. in *Science,* Vol. 312, pages 400–404; April 21, 2006.

Learning how rats escape from cats also reveals how a storm of electrical pulses sweeping across the brain is translated into information

SEEKING the

By Miguel A. L. Nicolelis and Sidarta Ribeiro

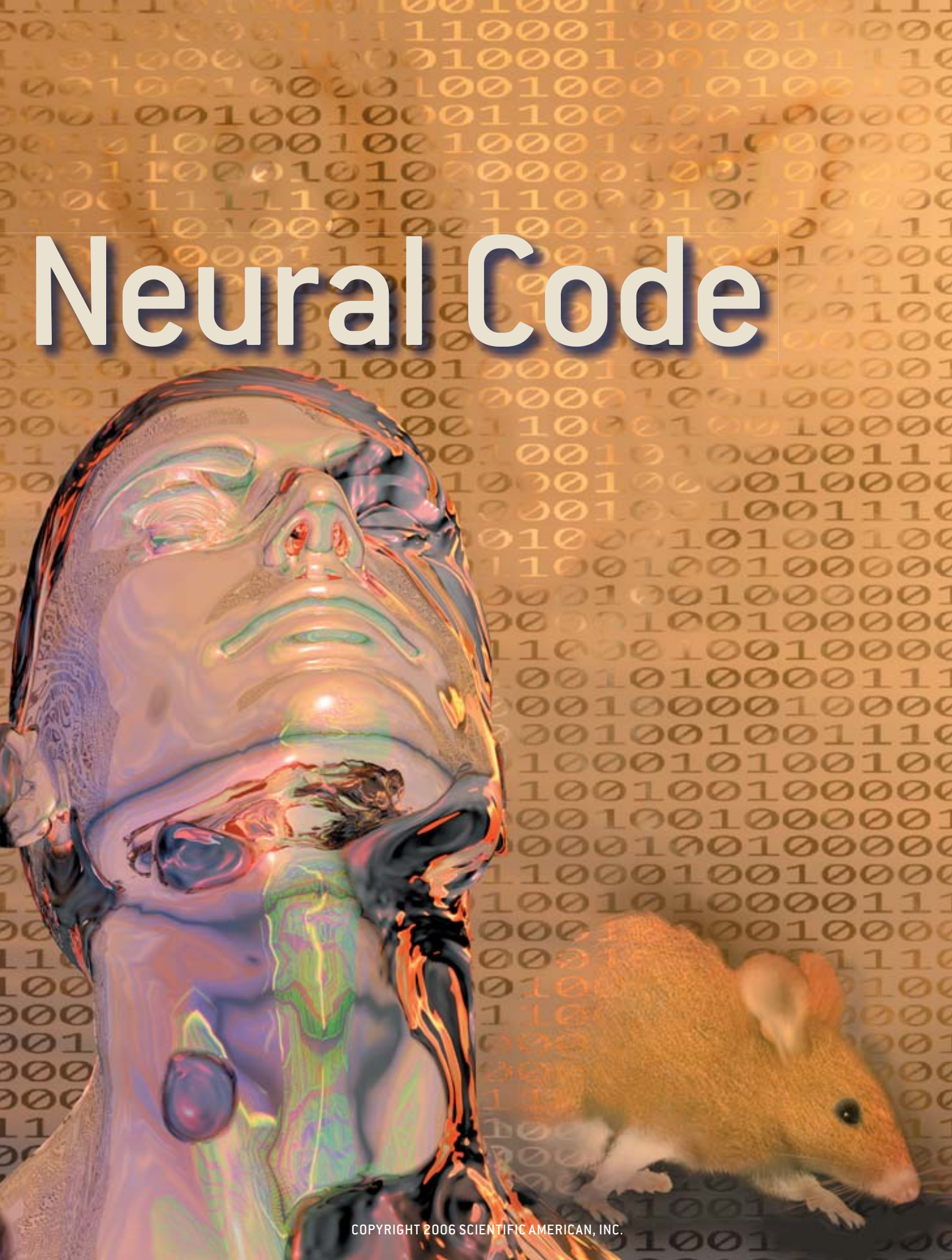
As the computer-controlled sliding doors suddenly opened, revealing a pitch-dark but already familiar chamber, Eshe did exactly what was expected of her after all those demanding weeks of training. Without hesitation—and most likely counting on the reward she was certain to receive given her superb performance of late—she lunged into the narrow room moving at full speed toward the opposite wall. She was ready to show off her skills.

The trial started the moment Eshe crossed an infrared light beam in front of an aperture positioned directly in her running path. The opening, flanked by the small arms of two T-shaped metal bars protruding from each side of the chamber, defined a slot through which Eshe had to pass to reach the opposite wall. Her job was far from trivial: in total darkness she had to estimate, in a single attempt, the aperture's diameter as quickly as possible. To make things more complicated and interesting, the opening's size varied randomly from trial to trial. Without being able to see the bars, Eshe had only one way to achieve her goal—she had to rely entirely on her exquisite sense of touch.

Amazingly, even when the aperture's diameter varied by only a couple of millimeters, Eshe could correctly discriminate in 90 percent of trials whether it was narrower or wider than before. And she solved this tactile riddle in barely 150 milliseconds by touching the edges of both bars with only the tips of the prominent long hairs that sprouted from both sides of her face. From a human perspective, Eshe's trick was no small feat. Anyone trying to solve a similar task by applying a mustache or beard to the same aperture would have failed miserably.

But Eshe was a rat, and the base of each of her whiskers contained a very high density of specialized peripheral sensory organs, known as mechanoreceptors, which translate the main

Neural Code



attributes of tactile stimuli into a language that the brain can understand: electricity. In rats, as in people, such electrical signals are conveyed by a multitude of peripheral nerves throughout the body into multiple interconnected brain structures, forming a vast neural circuit known as the somatosensory system, which accounts for our broad repertoire of tactile sensations. This same vast circuit also contributes to the genesis of our most intimate perceptual experience: our own sense of self.

Yet exactly how the brain translates a language of electrical pulses into such fine and varied perceptions has long been a profound puzzle and one of the holy grails of brain research. To crack this neural code is to open the doors to comprehending the essence of who we are. Our abilities to speak, love, hate and perceive the world around us, as well as our memories, our dreams, even our species history, emerge from the combination of a multitude of tiny electrical signals that spread across our brains, just like a thunderstorm sweeps the sky on a summer night.

Deceptively Straight Lines

WITHOUT KNOWING IT, Eshe had been participating in an experiment designed to address this very central question. That she decided to use her facial hair to solve her task was only proper. When rats really need to escape from cats, dashing through an opening of uncertain size located somewhere in the wall of a dark, unfamiliar place, whiskers offer their best hope to succeed.

A rat's mechanoreceptors translate any minute mechanical deflection of the whiskers into fast sequences of small electrical discharges, known as action potentials, to signal the location, intensity and duration of tactile stimuli. These pulses are transmitted to the brain via the trigeminal system, a nerve network that is the part of the somatosensory system specializing in conveying and processing tactile signals from the face. Understanding how Eshe and other rats can so readily compute an aperture's diameter in a mere fraction of a second, using only tactile information gathered by their whiskers, therefore rests on elucidating how vast populations of neurons distributed across the trigeminal system interact to process this incoming sensory information.

Researching this question, of course, reveals a lot more than simply how anxious rats elude hungry cats. Indeed, since the early 1970s neurophysiologists have studied the rodent trigeminal system to try to answer fundamental questions about the nature of neural coding. The work of our laboratory and many others around the world toward deciphering the code illustrates just how dramatically hypotheses have evolved since that time, as well as how much more we have yet to learn.

Three decades ago the theory favored by most neuroscientists was known as the labeled-line model because it proposed that sensory information generated at the body's periphery is conveyed through multiple parallel neural pathways all the way to the brain's neocortex. In essence, the message would travel through a strict feedforward circuit connecting peripheral sensory receptors, such as facial whiskers, to higher-order structures in the brain.

That paradigm received a significant boost during the 1970s, when Tom Woolsey and Hendrik Van der Loos, neuroanatomists at the Johns Hopkins University School of Medicine, revealed what appeared to be the trigeminal system's physical lines of communication within the primary somatosensory cortex (S1) of the mouse brain. As in other mammals, the mouse cortex can be divided into six layers based on each one's distinctive texture and distribution of nerve cell types and numbered I to VI from the outermost brain surface to the innermost cortical layer. By extracting blocks of tissue containing the whole S1 cortex of a mouse, Woolsey and Van der Loos were able to produce thin tangential slices spanning the entire cortical width and then stain those tissue sections for the presence of cytochrome oxidase (CO), a mitochondrial enzyme associated with intensive cellular activity.

To their surprise, Woolsey and Van der Loos found that cortical layer IV contained multiple distinct clusters of CO-rich neurons in a well-delineated arrangement of rows and columns. Thousands of tightly packed neurons made up each barrel-shaped cluster, prompting the researchers to call a single cluster a barrel and the entire matrix the "barrel field." Most astonishingly, this barrel field defined a beautiful, if slightly distorted, map of the mouse's snout.

A similar barrel-field arrangement was soon found in the rat cortex [*see box on opposite page*], and further studies revealed such topographic maps in subcortical structures, including the brain stem and thalamus, where the clusters were dubbed barrelets and barreloids. Indeed, stacks of these topographic maps at each of the subcortical relays of the trigeminal system were shown by subsequent investigators to link the peripheral sensory receptors in the facial whiskers of rats all the way up to the S1 cortex.

Sensory neurophysiologists use the term "receptive field" to define the amount of skin that when stimulated causes a neuron to respond by producing action potentials. In the case of the

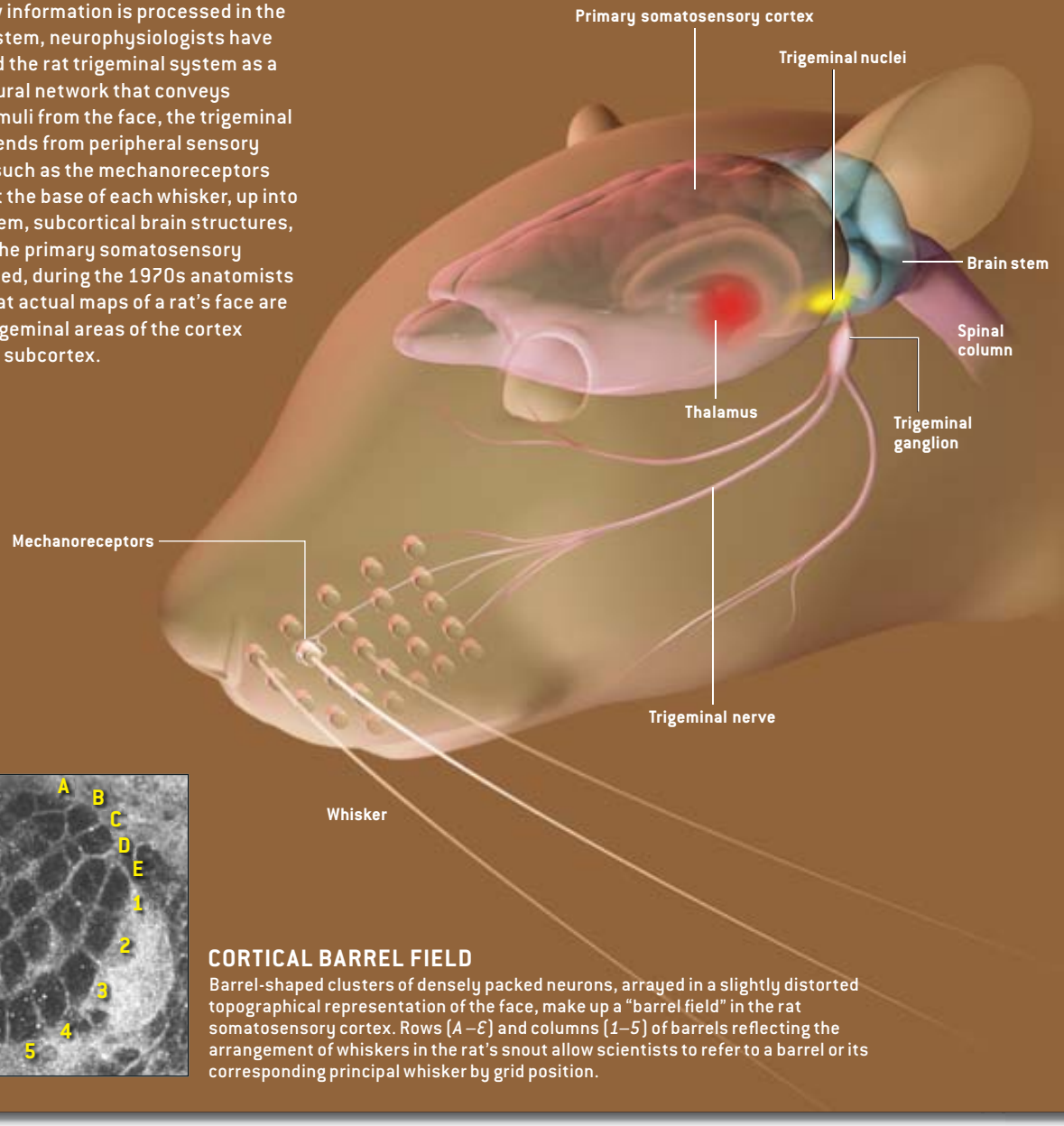
Overview/*An Emerging Code*

- Storms of electrical pulses sweeping through the central nervous system somehow translate into thoughts, emotions and sensations. Neuroscientists have spent decades trying decipher this neural language.
- Early hypotheses about sensory perception envisioned strictly linear transmission of signals along discrete neural routes between stimulus receptors and higher processing centers in the brain.
- Monitoring large populations of neurons in sensory pathways has revealed instead that information is encoded in the spatiotemporal activity patterns of entire neural ensembles.

PHIL SAUNDERS *Space Channel Ltd.* [*preceding pages*]

A SENSORY NETWORK

To learn how information is processed in the nervous system, neurophysiologists have long studied the rat trigeminal system as a model. A neural network that conveys sensory stimuli from the face, the trigeminal system extends from peripheral sensory receptors, such as the mechanoreceptors clustered at the base of each whisker, up into the brain stem, subcortical brain structures, and finally the primary somatosensory cortex. Indeed, during the 1970s anatomists revealed that actual maps of a rat's face are visible in trigeminal areas of the cortex (*below*) and subcortex.



CORTICAL BARREL FIELD

Barrel-shaped clusters of densely packed neurons, arrayed in a slightly distorted topographical representation of the face, make up a "barrel field" in the rat somatosensory cortex. Rows (*A*–*E*) and columns (*1*–*5*) of barrels reflecting the arrangement of whiskers in the rat's snout allow scientists to refer to a barrel or its corresponding principal whisker by grid position.

GARY CARLSON (*illustration*); COURTESY OF HERB KILLACKEY, FROM "ORGANIZATION OF CORTICOCORTICAL CONNECTIONS IN THE PARIETAL CORTEX OF THE RAT" IN *JOURNAL OF COMPARATIVE NEUROLOGY*, VOL. 181, NO. 3; 1978 (*micrograph*)

rodent somatosensory system, therefore, the most important prediction of the labeled-line model was that the receptive field, or spatial domain, of a single neuron located in one of these trigeminal barrels would be restricted to a single principal whisker.

By the late 1980s, however, contradictory results began to challenge this neat linear view. For instance, neurophysiologist Michael Armstrong-James, then at the University of London, recorded the activity of individual neurons located in multiple cortical barrels of anesthetized rats. Although he could identify the principal whisker of most of these cortical neurons, he also showed that an individual neuron was able to respond to deflection of whiskers surrounding that principal whisker.

In an almost heretical conclusion for the time, Armstrong-James suggested that the receptive fields of single neurons in the rat barrel cortex were not confined to single primary whiskers. Instead the neurons' spatial domains included a few surrounding whiskers, which, when deflected, drove neurons to produce weaker and slower—but still highly significant—tactile responses. This idea was enough to trigger a major controversy in the field, yet it was just the beginning of what would be a transformative decade for scientists' understanding of neural coding.

Distributed Computing

THE TECHNIQUE employed by Armstrong-James to record the activity of

single neurons, one at a time, in anesthetized rats was more or less state of the art in 1989 when one of us (Nicolelis) and John K. Chapin, now at the State University of New York Downstate Medical Center, decided to apply a new method for listening to the electrical activity of multiple individual neurons simultaneously.

We focused initially on neurons located in the barreloids of the ventral posterior medial (VPM) nucleus, a structure within the thalamus that is the main source of ascending nerve connections to the barrel fields of the primary somatosensory cortex. Our first studies showed that those VPM neurons exhibited very large, multiwhisker receptive fields. Much as Armstrong-James had found in the cortex, the VPM neurons' strongest and fastest responses resulted from deflection of each one's principal whisker, defining the center of its receptive field, while weaker and slower responses were triggered by stimulation of surrounding whiskers.

In fact, as rats became less and less anesthetized and finally fully awake, the size of individual VPM neurons' receptive fields increased significantly, sometimes including most of the facial whiskers on the same side of the rat's face. Moreover, because the VPM neurons responded with different latencies, or delays, to stimulation of different whiskers, the spatial domain of each neuron's receptive field shifted as a function of poststimulus time. In other words, we literally could not define the center and boundaries of a given neuron's receptive field *unless* we specified a particular moment in time.

This dynamic spatiotemporal aspect of the neurons' responses also allowed the cells to quickly reorganize their reactions immediately after any change in the flow of tactile information from the periphery. By simply anesthetizing small patches of skin in the rat's face, for example, we were able to see within a few seconds a complete reorganization of the receptive fields of VPM neurons to accommodate the new pattern of incoming tactile information.

We followed these findings with even more technically challenging experiments involving simultaneous monitoring of the activity of larger samples of individual neurons in multiple brain stem, thalamic and cortical relays of the rat trigeminal system. Our concurrent multisite, multielectrode recordings yielded simultaneous samples of up to 48 single neurons per animal, distributed across up to five different neural structures.

This was the first time such a comprehensive spatial sampling of an animal's sensory pathway had ever been performed. And the result was as clear as it was shocking: single whisker deflections in awake animals triggered complex

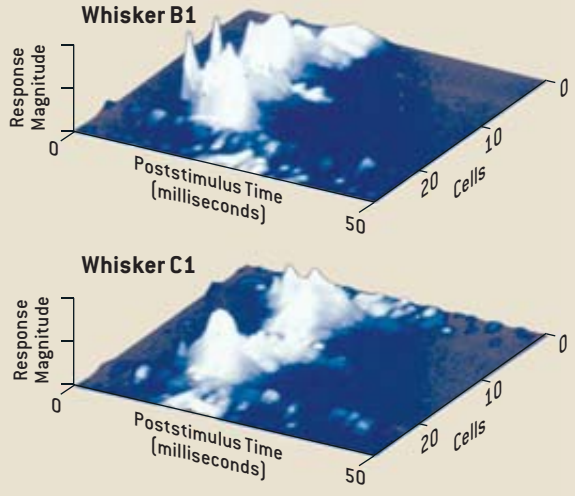
COURTESY OF *NEURON*, VOL. 18; APRIL 1997 (*left and center*); MELISSA THOMAS (*bottom right*)

CONVERGING SIGNALS

Stimulating individual whiskers on the face of a rat reveals a complex network of reactions distributed across populations of neurons and over time. Sensory information from a single whisker is thus encoded in the spatiotemporal pattern of responses by a multitude of cells throughout the animal's trigeminal system.

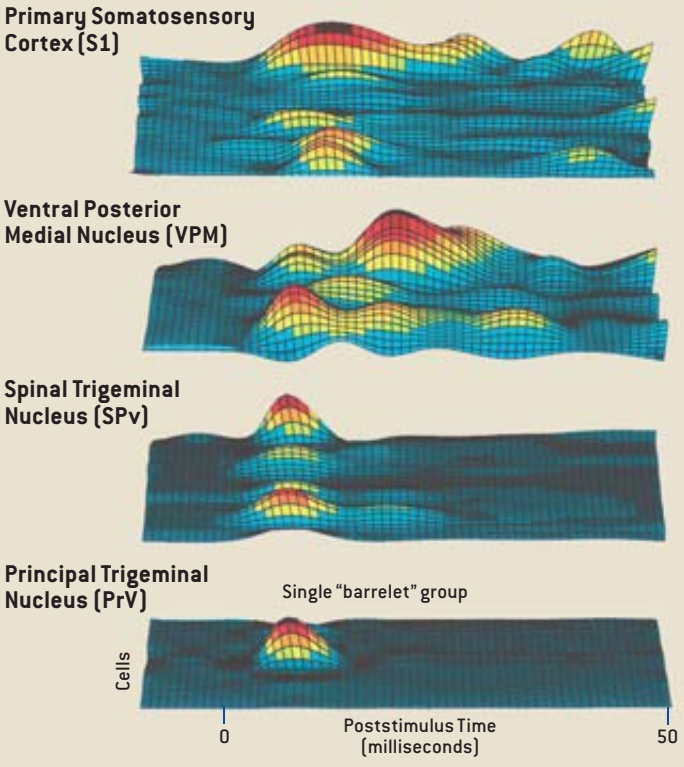
NEURON POPULATION RESPONSES

Instead of responding only to one principal whisker, 25 neurons in various cortical barrel columns react to the stimulation of different whiskers with distinct response profiles (*below*). Each row depicts a single cell's electrical activity after whisker stimulation.

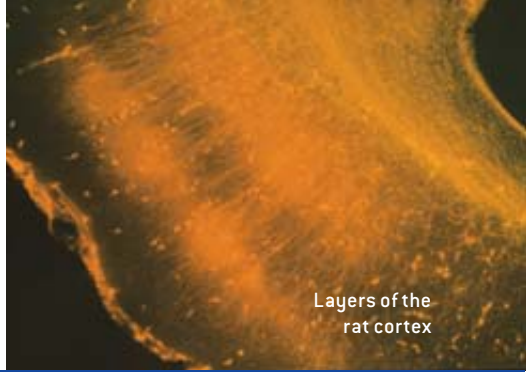


CELL GROUP RESPONSES

Stimulation of a single whisker produces waves of electrical activity in barrel-shaped cell clusters within the brain stem (SPv and PrV), thalamus (VPM) and cortex (S1).



Only by combining the activity of neuron populations would the brain extract meaningful information.


Layers of the rat cortex

MIGUEL A. L. NICOLELIS

waves of electrical activity that spread across multiple barrel-shaped clusters within each of the neural structures along the trigeminal system [*see box on opposite page*]. What we were observing was not at all consistent with information traveling along static, segregated, labeled lines. Instead our findings suggested an alternative model known as a distributed representation or a population neural code: only by combining the activity of large populations of single neurons would the rat brain be capable of extracting precise and meaningful tactile information about the animal's immediate surrounding environment.

To test this observation further, Asif Ghazanfar, a graduate student in our lab in the mid-1990s, attempted to "read" the coded messages sent by trigeminal neuron populations in a rat. He did this by feeding the activity of many cortical neurons, obtained during mechanical stimulation of multiple individual whiskers, to a series of artificial pattern-recognition algorithms known as artificial neural networks (ANNs). First Ghazanfar trained an algorithm to use the spatiotemporal firing patterns of entire populations of cortical neurons to correctly classify the location of single-whisker stimuli. Once the ANN reached a high level of accuracy, he introduced a new data set, then measured how well the algorithms could predict the location of a stimulated whisker. When the ANNs were fed the activity of single neurons in isolation, the accuracy of their predictions was extremely low. But when they had the combined responses of populations of individual neurons, the algorithms could easily predict the correct location of a whisker stimulus in a single trial.

By this time, other laboratories using a variety of methods were also obtaining data that supported our electrophysiological findings. And Ghazanfar, along with postdoctoral fellow David Krupa, went on to demonstrate for the first time that blocking neuron activity in the S1 cortex affected the responses of VPM neurons in the thalamus, suggesting that descending or feedback signals from the cortex to the VPM could also play a major role in modulating the ascending information from the brain stem. These and similar results together led our group to propose that the highly dynamic multiwhisker tactile responses seen in both S1 and VPM neurons were determined by a multitude of ascending, descending, lateral and modulatory signals that converge at each of these neurons at a different moment in time.

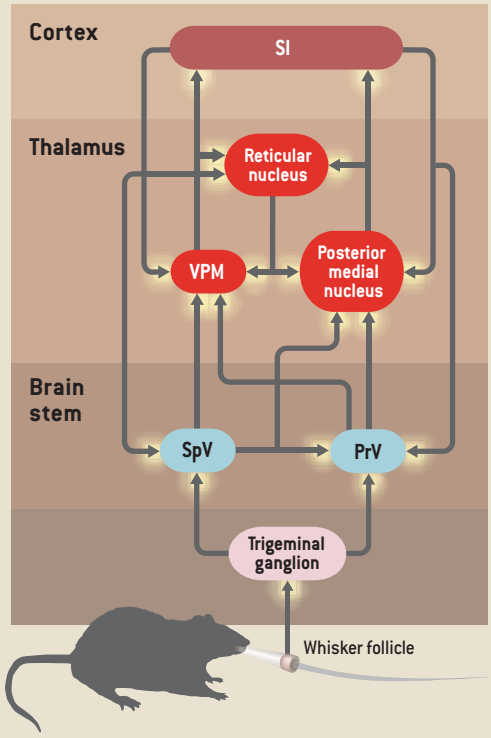
Our findings were already a far cry from the strict feedforward, labeled-line theory. But many predictions derived from our asynchronous convergence model still required extensive experimental testing, which led us into yet another decade-long journey of stimulating rat whiskers in a variety of ways that had never been tried before.

Context Counts

IN 1998 a graduate student in our laboratory, Erika Fanselow, designed a clever technique to measure how the S1 and VPM neurons would respond to similar tactile stimuli received under different conditions in freely moving rats. By im-

TRIGEMINAL SIGNAL PATHWAYS

Incoming tactile signals from a whisker are modulated by neural signals traveling along lateral and descending connections between brain structures.



THE AUTHORS

MIGUEL A. L. NICOLELIS and *SIDARTA RIBEIRO* investigated neural coding together when Ribeiro was a postdoctoral fellow in Nicolelis's laboratory at Duke University. As co-director of Duke's Center for Neuroengineering and Anne W. Deane Professor of Neuroscience, Nicolelis has pioneered the use of multielectrode brain implants to eavesdrop on the activity of large numbers of neurons and the development of computational methods to interpret and apply the results. Both Brazilian-born and avid soccer fans, Nicolelis and Ribeiro also share a passion for disseminating the benefits and resources of cutting-edge neuroscience. They are co-founders of the International Institute of Neuroscience of Natal in northeastern Brazil. Ribeiro is scientific director of the César Timo-Iaria Research and Education Center, a division of the institute, which ultimately plans to combine a world-class neuroscience research and training facility with a school, mental health and athletic facilities, a science museum and a conservation park to foster social and economic development in the remote region.

planting a tiny cuff electrode around the infraorbital nerve, the trigeminal nerve branch leading from the facial whiskers, Fanselow could deliver precise sequences of electrical pulses to the nerve while simultaneously measuring the responses of neurons in S1 and the VPM. She then measured how those neuronal responses varied during different behaviors exhibited by rats going about their daily routines. These experiments revealed that when rats were moving their whiskers, their cortical and thalamic neurons responded to tactile stimuli in a very different way than when the same animals were quietly awake or anesthetized.

In quiet rats, these neurons classically responded to stimulation with a brief sequence of action potentials, followed by a long-lasting period when their firing was inhibited by changes in their cell membranes. Fanselow found, however, that when the rats produced whisker movements of any kind, their cortical and thalamic neurons fired more steadily in response to a single electrical nerve pulse, without any periods of inhibition.

This observation prompted her to try delivering sequences of two electrical pulses to the nerve instead of just one, and the result was astounding. When rats were awake but immobile and not moving their whiskers, their cortical and thalamic neurons could respond only to the first stimulus of a pair; the second was masked by postexcitatory inhibition. But when rats were actively moving their whiskers, their S1 and VPM neurons could respond very well to both electrical pulses, even when separated by as little as 25 microseconds. Engaging in the whisking behavior clearly changed properties of the neurons, allowing both the cortex and the thalamus to faithfully represent a sequence of tactile stimuli.

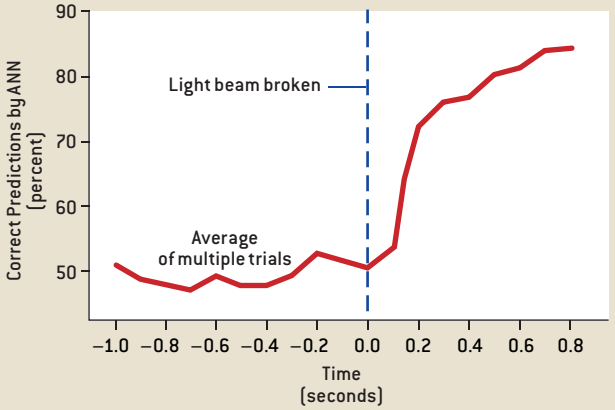
Around this time, Krupa was starting to succeed in training rats to perform the same task that Eshe would master so well a few years later. This method offered a new way to test whether neuron responses would also differ when the animal's active tactile discrimination task was more meaningful and demanding—more like real life—such as using its facial hair to judge the ever changing diameter of a hole.

His results confirmed and expanded on Fanselow's earlier observations: when animals actively used their whiskers to judge the diameter of the aperture, a large percentage of their S1 and VPM neurons exhibited intense, long-lasting responses without inhibition. Moreover, several neurons in the cortex clearly started to modulate their firing rates well before the rats' whiskers touched the edges of the bars, suggesting that the animals' behavioral state was already influencing properties of the neurons, priming them for the crucial task ahead.

As a final demonstration that these effects were also part of the encoded information feeding forward and backward within the animal's sensory system, Krupa fed the spatiotemporal firing patterns of neuron populations recorded during the execution of this task to an artificial neural network. With the combined activity of up to 50 cortical neurons, the ANN could predict with great

READING THE MIND OF A RAT

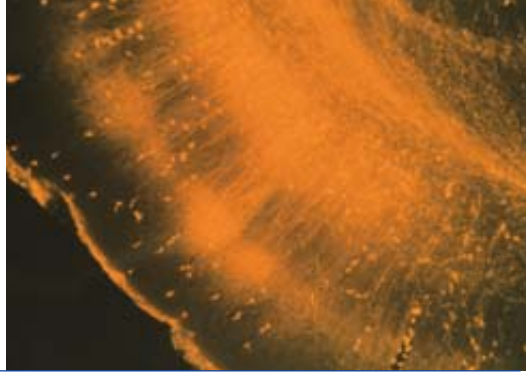
The ability to predict a rat's behavior demonstrates that a pattern-recognition algorithm can decipher sensory information encoded in the animal's neural activity. When fed recordings from the brains of rats participating in the experiment shown at the right, an artificial neural network (ANN) could determine whether an animal would correctly discern the width of an opening. As might be expected, the ANN performed (*graph*) at the level of chance before the rats broke a light beam at the entrance to the experimental chamber (zero seconds). After the animals began exploring the opening with their whiskers (0.1 to 0.25 second), the algorithm's prediction accuracy rose rapidly.



IN THE EXPERIMENT, a rat used its whiskers to feel an aperture formed by two movable bars flanking a nose poke. The animal then reported its judgment about the size of the opening by seeking a reward in an outer chamber at one of two stations it was trained to associate with "narrow" or "wide."

MELISSA THOMAS (*graph*); SOURCE: DAVID J. KRUPA ET AL. IN *SCIENCE*, VOL. 304, PAGES 1989–1992; JUNE 25, 2004 (*graph* and *photographs*)

How can our brains endow each of us with such a unique and irreproducible existence?



accuracy whether rats were going to correctly identify a wide versus a narrow aperture on any given try.

Dynamic Network

OUR ABILITY TO PREDICT the animal's behavior from neural firing patterns alone suggested that we were on the right track toward learning to interpret the language of the nervous system. It was already abundantly clear that instead of relying solely on the activity of specialized individual neurons or even linear columns of barrel-shaped modules, the mammalian brain more likely depends on highly distributed neural ensembles, dynamically formed by broadly tuned cells, to endow animals with their exquisite perceptual capabilities.

A single neuron's membership in those ensembles is probably fluid and might change from moment to moment, and one neuron can participate in many of these assemblies simultaneously. An individual cell's firing properties can also change continuously as a result of the state of the sensory periphery, the animal's past perceptual experiences, its internal brain dynamics, whether it is actively or passively sampling its environment, and the animal's expectations for the future.

We humans share with rats the same basic features of brain architecture, physiology and cell biology. And like them, we navigate our sensory environment aided by complex neural networks producing multiple representations of the surrounding world, shaping perception from moment to moment on a minute scale according to variations in attention, motivation and mood and taking into account our previous sensory experiences.

But how do all these by-products emerge from the tiny electrical discharges of billions of neurons? How can our brains make us all behave so similarly at times and yet endow each of us with such a unique and irreproducible existence? Most neuroscientists would agree that the intricate details of that puzzle will remain a profound mystery for some time.

Yet our research group's work toward deciphering the neural code has already allowed us to put our cursory understanding of this language to practical use by reading neural firing patterns from the motor cortex of a monkey and using computer algorithms to translate that information, in real time, into instructions for moving a robot arm [see "Controlling Robots with the Mind," by Miguel A. L. Nicolelis and John K. Chapin; SCIENTIFIC AMERICAN, October 2002]. Our hope is that one day soon we will also master sufficient syntax to talk back to the brain, which would allow us, for example, to build a human prosthetic arm laden with sensors to send tactile feedback into the somatosensory cortex of its user.

Although the neural code is far from cracked, we are able to catch, and to speak, a few syllables now, and that was not true just 10 years ago. One important reason that we can already use this idiom is its inherent adaptability, which in turn stems from the network properties of communication through neural ensembles. Even if a few words are dropped, the message still comes across, much the way a robust technological network can rapidly compensate for the loss of a few nodes.

Another crucial influence on progress in this field has been the evolution of basic experimental equipment. Decades ago neuroscientists were limited to recording lone neurons, using stiff metal electrodes that damaged brain tissue if moved too violently. As a result, investigators were also forced to study brain activity while an animal was anesthetized or at least sedated and restrained. As our own group's experience demonstrates, once scientists could listen to dozens of neurons in multiple brain structures simultaneously, a new population-based view of neural activity was possible. And new flexible electrode materials made permanent implantation of recording devices in the brain feasible, permitting us today to listen in on the activity of as many as 500 individual neurons, over long periods, in an awake animal engaging in normal behaviors.

It is perhaps no wonder that monitoring neurons one at a time encouraged a linear, neuron-centric view of neural communication. Those early methods could be compared to hearing only one voice during the performance of an opera—no matter how talented the soloist, one would still find it hard to follow the story. When combined into large and widely distributed neural ensembles, however, the collective interactions of these neurons yield exquisitely accurate descriptions of our surrounding environment. Thus, whenever a rat escapes another charging cat, its salvation is most likely thanks to a symphony of electrical pulses playing in its head. SA

MORE TO EXPLORE

Brain-Machine Interfaces to Restore Motor Function and Probe Neural Circuits. Miguel A. L. Nicolelis in *Nature Reviews Neuroscience,* Vol. 4, pages 417–422; May 2003.

Layer-Specific Somatosensory Cortical Activation during Active Tactile Discrimination. David J. Krupa et al. in *Science,* Vol. 304, pages 1989–1992; June 25, 2004.

Global Forebrain Dynamics Predict Rat Behavioral States and Their Transitions. Damien Gervasoni, Shih-Chieh Lin, Sidarta Ribeiro, Ernesto S. Soares, Janaina Pantoja and Miguel A. L. Nicolelis in *Journal of Neuroscience,* Vol. 24, No. 49, pages 11137–11147; December 8, 2004.

International Institute of Neuroscience of Natal: **www.natalneuroscience.com**

MIGUEL A. L. NICOLELIS

SPECIAL REPORT

An earlier version of this story was posted on www.sciam.com. Readers were invited to send in their comments and questions, and scientists were asked to provide commentaries. That feedback helped to shape the article that follows.

AN EXTRAORDINARY NEW HUMAN FOSSIL RENEWS DEBATE OVER THE EVOLUTION OF UPRIGHT WALKING

LUCY'S BABY

BY KATE WONG

The arid badlands of Ethiopia's remote Afar region have long been a favorite hunting ground for paleoanthropologists. Many hominins—the group that includes all the creatures in the human line since it branched away from that of the chimps—once called it home. The area is perhaps best known for having yielded "Lucy," the 3.2-million-year-old skeleton of a human ancestor known as *Australopithecus afarensis*. Now researchers have unveiled another incredible *A. afarensis* specimen from a site called Dikika, just four kilometers from where Lucy turned up. But unlike Lucy, who was well into adulthood by the time she died, the new fossil is that of an infant, one who lived 3.3 million years ago (and yet has nonetheless been dubbed "Lucy's baby").

BABY FACE: The recently unveiled skeleton of a juvenile *Australopithecus afarensis* nicknamed Selam is more complete than even the well-known Lucy fossil. And whereas much of Lucy's face is missing, Selam's is exquisitely preserved.

No other hominin skeleton of such antiquity—including Lucy—is as complete as this one. Moreover, as the earliest juvenile hominin ever found, the Dikika child provides an unprecedented opportunity to study growth processes in our ancient relatives. "If Lucy was the greatest fossil discovery of the 20th century," says Donald C. Johanson of Arizona State University, who unearthed the famed fossil in 1974, "then this baby is the greatest find of the 21st thus far."

Bundle of Joy

IT WAS THE AFTERNOON of December 10, 2000, when fossil hunters led by Zeresenay Alemseged, now at the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany, spotted the specimen. Only part of its tiny face was visible; most of the rest of the skeleton was entombed in a melon-size block of sandstone. But "right away it was clear it was a hominin," Alemseged recollects, noting the smoothness of the brow and the small size of the canine teeth, among other humanlike characteristics. Further evaluation, however, would have to wait until the fossil was cleaned—a painstaking process in which the cementlike matrix is removed from the bone almost grain by grain with dental tools.

> "You don't just magically flip some evolutionary switch somewhere and transmute a quadruped into an upright-walking bipedal human."
>
> —*Donald C. Johanson*

It took Alemseged five years to expose key elements of the child's anatomy; many more bones remain obscured by the sediment. Still, the find has already surrendered precious insights into a species that most researchers believe gave rise to our own genus, *Homo*. Alemseged and his colleagues described the fossil and its geologic and paleontological context in two papers published in the September 21 *Nature*. And at a press conference held in Ethiopia to announce the discovery, they christened the child Selam—"peace" in several Ethiopian languages—in hopes of encouraging harmony among the warring tribes of Afar.

The skeleton, judged to be that of a three-year-old girl, consists of a virtually complete skull, the entire torso, and parts of the arms and legs. Even the kneecaps—no larger than macadamia nuts—are preserved. Many of the bones are still in articulation. Hominin fossils this complete are incredibly rare, and ones of infants are rarer still because their bones are that much more fragile. Indeed, the next oldest skeleton of a juvenile that is comparably intact is a Neandertal baby dating to around 50,000 years ago.

Walking vs. Climbing

THE EXCEPTIONAL PRESERVATION of Selam, as well as that of other animals found at the site, indicates to team geologist Jonathan G. Wynn of the University of South Florida that her body was buried shortly after death by a flood event. Whether she perished in the flood or before it is unknown.

Although she was only three when she died, Selam already possessed the distinctive characteristics of her species. Her projecting snout and narrow nasal bones, for example, readily distinguish her from another ancient youngster, the so-called Taung child from South Africa, who was a member of the closely related *A. africanus* species. And her lower jaw resembles mandibles from Hadar, the site where Lucy and a number of other *A. afarensis* individuals were found.

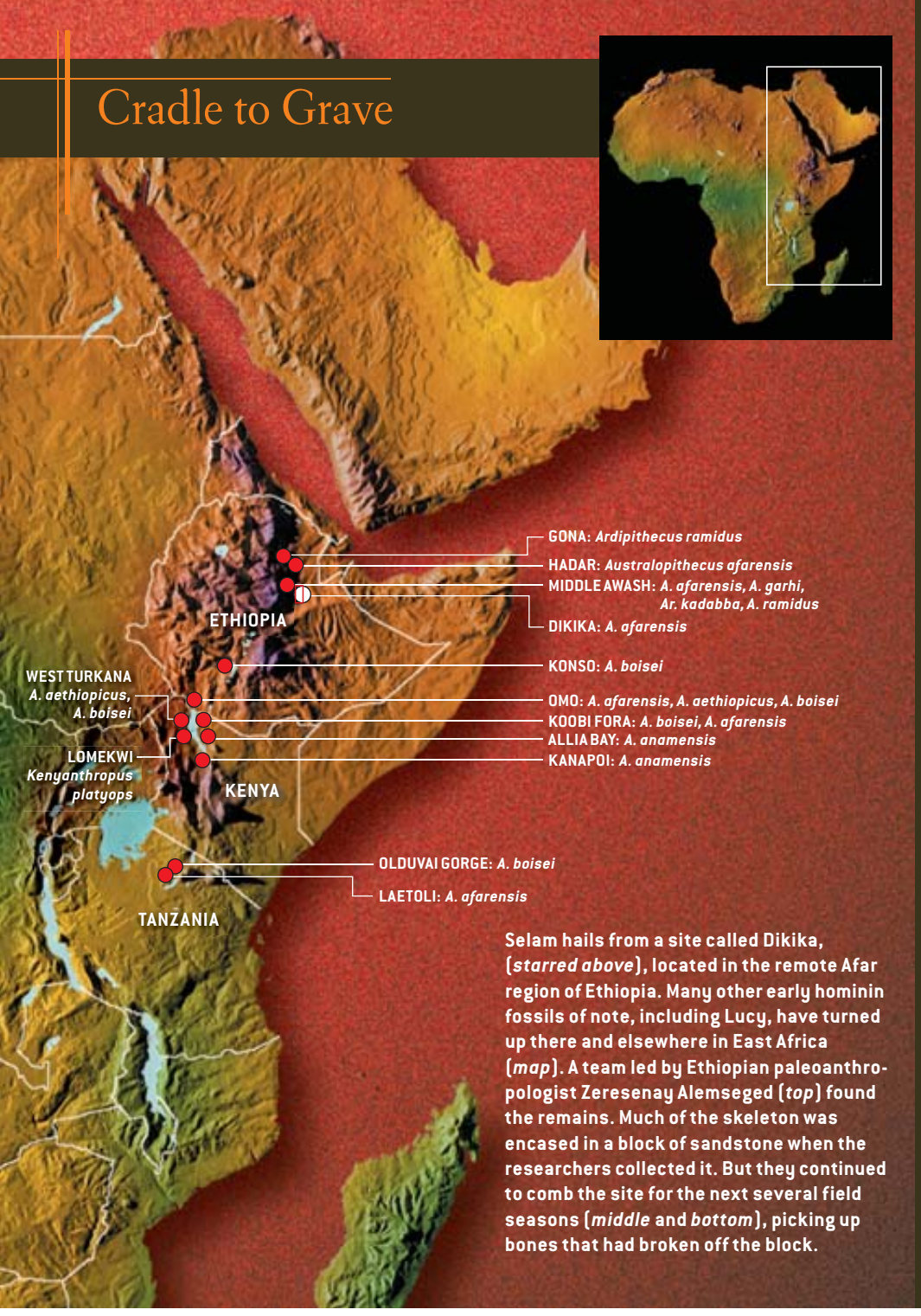
Selam also exhibits the same mash-up of traits in her postcranial skeleton that has long vexed scientists interested in how *A. afarensis* moved around the landscape. Scholars agree that *A. afarensis* was a creature that got around

Overview/*The Earliest Child*

- Researchers working in northeastern Ethiopia have found the remains of a baby *Australopithecus afarensis,* a species believed to be ancestral to our own.
- Some 3.3 million years old, the spectacularly complete skeleton is the earliest child in the human fossil record.
- Preserving bones never before known for *A. afarensis,* the specimen is raising questions about how our ancestors became bipedal.
- The Dikika infant may also illuminate the order in which other body parts changed over the course of human evolution.

NATIONAL MUSEUM OF ETHIOPIA, ADDIS ABABA (*preceding page*)

Cradle to Grave



Selam hails from a site called Dikika, (*starred above*), located in the remote Afar region of Ethiopia. Many other early hominin fossils of note, including Lucy, have turned up there and elsewhere in East Africa (*map*). A team led by Ethiopian paleoanthropologist Zeresenay Alemseged (*top*) found the remains. Much of the skeleton was encased in a block of sandstone when the researchers collected it. But they continued to comb the site for the next several field seasons (*middle* and *bottom*), picking up bones that had broken off the block.

EDWARD BELL (*map*); DENNÉ REED *University of Texas at Austin* (*top* and *bottom*); JONATHAN G. WYNN *University of St. Andrews* (*middle*)

capably on two legs. But starting in the 1980s, a debate erupted over whether the species was also adapted for life in the trees. The argument centered on the observation that whereas the species has clear adaptations to bipedal walking in its lower body, its upper body contains a number of primitive traits better suited to an arboreal existence, such as long, curved fingers for grasping tree branches. One camp held that *A. afarensis* had made a full transition to terrestrial life and that the tree-friendly features of the upper body were just evolutionary baggage handed down from an arboreal ancestor. The other side contended that if *A. afarensis* had retained those traits for hundreds of thousands of years, then tree climbing must have still formed an important part of its locomotor repertoire.

Like her conspecifics, Selam has legs built for walking and fingers built for climbing. But she also brings new data to the controversy in the form of two shoulder blades, or scapulae—

Spectacular Skeleton

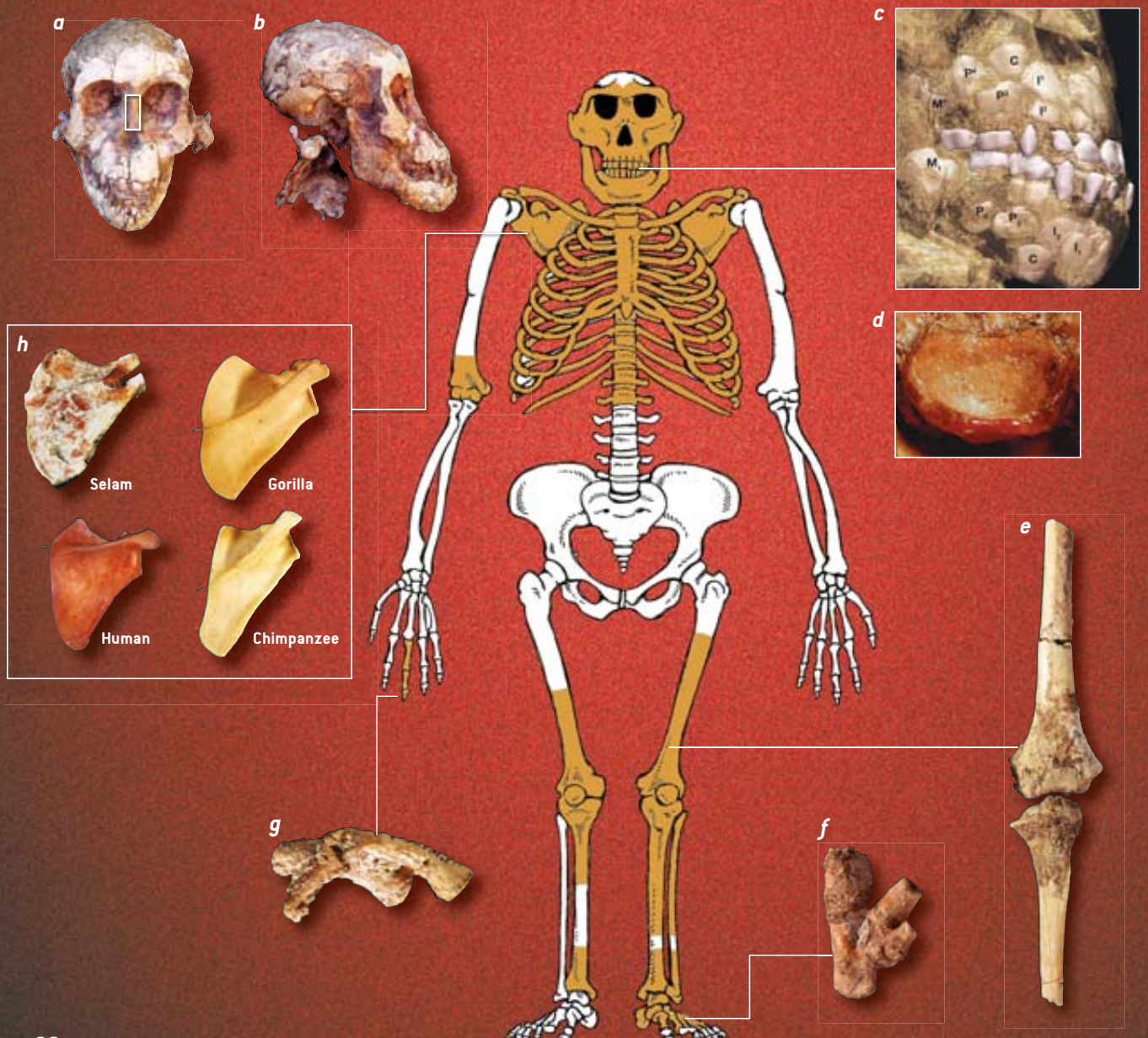
Selam is one of the most complete early hominin skeletons ever found, although many of the bones are still at least partially obscured by sandstone. In the drawing below, based on an adult *A. afarensis,* the bones believed to be present in the new specimen are shaded in gold.

Features of Selam's face, including the small, narrow nasal bones (*a*), identify her as *A. afarensis,* as opposed to the closely related *A. africanus.* Although much of the braincase is missing, the fossil preserves a natural sandstone endocast, or impression of the interior of the skull (*b*). The apparent brain size hints that *A. afarensis* may have had delayed brain growth relative to chimps, which is a characteristic of modern humans.

Computed tomography revealed that in addition to having a full set of milk teeth, the child had permanent teeth waiting to come in (*c*). The remains also include a delicate bone known as the hyoid (*d*), which helps to anchor the tongue and the voice box. It is only the second hominin hyoid ever found—the first came from a 60,000-year-old Neandertal skeleton. Its morphology suggests that *A. afarensis* had a chimplike voice box.

Like other *A. afarensis* individuals, Selam has a number of traits in her leg bones (*e*) and foot bones (*f*) that indicate she walked bipedally on the ground. Her heel, for example, exhibits a humanlike wideness. But her upper body seems partly adapted for life in the trees. She has long, curved fingers (*g*) that would have aided in grasping tree branches. And the socket of her shoulder blade, or scapula (*h*), faces upward like an ape's, rather than to the side like a human's.

The scapula is a bone of contention, however. According to the discoverers, it looks most like that of a gorilla. But critics charge that the bone is actually rather humanlike, particularly in the relative proportions of the depressed areas for muscle attachment on either side of the ridge that divides the blade.



PATRICIA J. WYNNE (*illustration*); FROM "A JUVENILE EARLY HOMININ SKELETON FROM DIKIKA, ETHIOPIA," BY ZERESENAY ALEMSEGED ET AL., IN *NATURE*, VOL. 443, SEPTEMBER 21, 2006 (*all bones*)

What readers want to know

In an earlier version of this article, posted on our Web site, we invited readers to submit any questions they had about Selam. Kate Wong answered their questions in the blog. An edited selection of those exchanges follow.

How was Selam's age at death assessed? —Stephen
A: Selam's age was estimated based on her apparent stage of dental development. Using comparable data from African apes, the researchers judged her to be about three years old when she died. But *Australopithecus afarensis* no doubt had a developmental schedule that differed from that of chimps and gorillas, so this is only an educated guess.

How was sex determined? —Debra Martin
A: The skeleton is believed to be that of a female based on computed tomographic measurements of the fully formed permanent tooth crowns still embedded in the jaws. When compared with measurements of teeth from *A. afarensis* individuals from the sites of Hadar, Laetoli and Maka, the Dikika child's teeth grouped closely with those of confirmed females.

What is the uncertainty of the measurement of the age of a fossil like Selam? What technology is used? —Juan Moreira
A: Diana C. Roman of the University of South Florida dated the fossil by ascertaining the ages of the layers of volcanic ash around Selam. One layer was deposited before the child died; the other was deposited some time after she died. By interpolating the position of the fossil relative to those two layers, Roman determined that the fossil was between 3.31 million and 3.35 million years old—an uncertainty of 40,000 years.

Has there been an x-ray or similar imaging done to determine what might remain? —Theresa Meade
A: The bones in the sandstone block are thought to have all been at least partly revealed, although it is possible there are some small bones buried in there. So it looks like it is really mostly a question of how complete the bones that have been partially cleaned are. The skull was subjected to CT scanning, which revealed the permanent teeth, as well as the morphology of the inner ear. But I don't know if the rest of the specimen was scanned.

What's the big deal? We know that our ancestors had to come down out of the trees sometime. Kids nowadays have a predilection for climbing trees, too. (Maybe an unconscious link to an arboreal past?) —Matthew T.
A: The question is to what extent *A. afarensis* was adapted for terrestriality. No one is suggesting that *A. afarensis* could not get up into a tree under any circumstances—as you correctly point out, humans can still do that—the debate is over whether it was adapted to do so. It's a big deal because bipedalism is a hallmark of human evolution, so paleoanthropologists are eager to understand the details of how it emerged.

Are there any plant or animal fossils associated with* A. afarensis *finds that would indicate what kind of environment they lived in? —Traveler
A: The animal fossils found at Dikika indicate that the child inhabited a moist, mosaic environment composed of woodlands and grasslands, with permanent water nearby. This is very similar to the environment in which Lucy and other representatives of *A. afarensis* lived.

What does the animal have to gain from being able to engage in endurance running? —Donald McMiken
A: Endurance running has been hypothesized to have given early humans a leg up (if you will) in hunting or scavenging, by allowing them to wear the prey out or reach the carcass faster, respectively.

bones previously unknown for this species. According to Alemseged, her scapulae look most like those of a gorilla. The upward-facing shoulder socket is particularly apelike, contrasting sharply with the laterally facing socket modern humans have. This orientation, Alemseged says, may have facilitated raising the hands above the head—something primates do when they climb. (Although gorillas do not climb as adults, they do spend time in the trees as youngsters.)

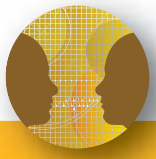
Further hints of arboreal tendencies reside in the baby's inner ear. Using computed tomographic imaging, the team was able to glimpse her semicircular canal system, which is important for maintaining balance. The researchers determined that Selam's semicircular canals are similar to those of African apes and *A. africanus*. This, they suggest, could indicate that *A. afarensis* was not as fast and agile on two legs as we modern humans are. It could also mean that *A. afarensis* was limited in its ability to decouple the movements of its head and torso, a feat that seems to play a key role in endurance running in our own species.

The conclusion that *A. afarensis* was a bipedal creature with an upper body at least partly adapted for life in the trees echoes what Jack T. Stern, Jr., of Stony Brook University and his colleagues wrote years ago in their reports on Lucy and her contemporaries. "I was happy to

see that this paper suggests I might have been right," Stern comments. Johanson agrees that the case for a partly arboreal *A. afarensis* is stronger than it once was. "Early on I was a staunch advocate of strict terrestrial bipedalism in *afarensis*," he remarks. But taking more recent findings into consideration, Johanson says, "it's not out of the realm of possibility that they were still exploiting some of the arboreal habitats for getting off the ground at night and sleeping up there or going back to familiar food sources."

A combination of walking and climbing would fit neatly with the picture that is emerging from studies of the environments of early hominins, including Selam. Today Dikika is an expanse of dusty hills dotted with only the occasional tree or shrub. But 3.3 million years ago, it was a well-watered delta flanked by forests, with some grasslands nearby. "In this context, it is not surprising to have an 'ape' that spends time in the trees and on the ground," comments project member René Bobe of the University of Georgia.

Not everyone is persuaded by the arboreal argument. C. Owen Lovejoy of Kent State University disputes the claim that Selam's scapula looks like a gorilla's. "It's primitive, but it's really more humanlike than gorillalike," he remarks. Lovejoy, a leading proponent of the idea that *A. afarensis* was a dedicated biped, maintains that the forelimb features that are typically held up as indicators that *A. afarensis* spent time in the trees only provide "evidence that the animal has an arboreal history." The discovery of the famed Laetoli footprints in 1978 closed the debate, he states. The trail did not show a prehensile big toe, without which, Lovejoy says, *A. afarensis* simply could not move about effectively in the trees.



What the experts are saying

We polled the experts for their thoughts on the discovery of Selam. Their views are encapsulated here. Go to www.sciam.com/ontheweb for the full comments.

JOHN HAWKS of the University of Wisconsin–Madison wonders whether Selam spells the end of a hotly contested hominin genus. In 2001 paleoanthropologists announced that they had found a fairly complete skull and some jaws and teeth at a site called Lomekwi in Kenya. They assigned the 3.5-million-year-old remains to a new genus of hominin, *Kenyanthropus.* Skeptics counter that the fossils are instead a regional variant of *A. afarensis.* It is an obvious sample with which to compare Selam. But oddly enough, no mention of *Kenyanthropus* appears in the formal description of the child.

RALPH L. HOLLOWAY of Columbia University hopes that the brain endocast will show enough details in the so-called Broca's regions and the occipital region to reveal a posterior placement of the lunate sulcus, a curved depression in the brain's surface. This would indicate a definite reorganizational pattern of the cerebral cortex toward a more humanlike rather than chimplike or gorillalike pattern.

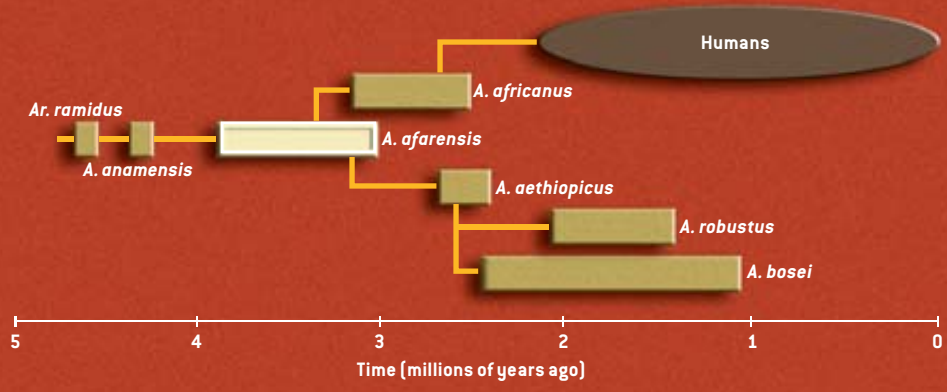
C. OWEN LOVEJOY of Kent State University makes the case that rather than reopening the debate over whether *A. afarensis* was a dedicated biped or whether it also spent some time in the trees, the Dikika child firmly closes it in favor of the species being strictly bipedal. Although the shoulder blade bears some resemblances to the gorilla shoulder blade, it actually shows some striking similarities with the human shoulder blade. Also, the fact that the youngster already had curved fingers at age three suggests that this is an inherited, primitive characteristic—as opposed to the individual having developed curved fingers as a result of grasping tree branches, which is what the arborealists envision.

RENÉ BOBE of the University of Georgia observes that one of the many important aspects of this fossil is that its geologic and paleontological context can be studied in detail. Dikika reveals hominin adaptations and environments that existed just before major climatic changes led to the ice ages, before *Homo* made its first appearance in the fossil record and before the earliest known stone tools. In Selam's day, Dikika was largely a lush, forested place. But by the time *Homo erectus* emerged, a little less than two million years ago, grasslands were much more prominent.

WILLIAM E. H. HARCOURT-SMITH of the American Museum of Natural History argues that features of Selam's upper limbs and inner ear are strong evidence that *A. afarensis* was partly arboreal. It will be very interesting, he says, to see whether analyses of her foot reveal that she was able to move her big toe so as to grasp branches. In his view, the first obligate bipeds were early members of our own genus, *Homo.*

An Ancient Ancestor

***A. afarensis* (*reconstruction at right*) is but one of many australopithecine species known to science. Researchers disagree about exactly how these species are related to one another, but most presume that *A. afarensis* was a precursor to our own genus (*below*).**



A Hodgepodge Hominin

EXPERTS MAY DISAGREE over the functional significance of Selam's apelike skeletal characteristics, but they concur that different parts of the hominin body were undergoing selection at different times. *A. afarensis* is "a good example of mosaic evolution," Johanson states. "You don't just magically flip some evolutionary switch somewhere and transmute a quadruped into an upright-walking bipedal human." It looks like natural selection is selecting for bipedalism in the lower limbs and pelvis first, and things that are not really used in bipedal locomotion, such as arms and shoulders, change at a later stage, he says. "We're getting to know more and more about the sequence of changes" that produced a terrestrial biped from a tree-dwelling, apelike creature.

Analysis of Selam's skull hints at a similarly piecemeal metamorphosis. The shape of the hyoid—a delicate, rarely preserved bone that helps to anchor the tongue and the voice box—indicates that *A. afarensis* had air sacs in its throat, which suggests that the species possessed an apelike voice box. Conversely, the child's brain shows a subtle sign of humanity. By studying the fossil's natural sandstone endocast, an impression of the braincase, Alemseged's team ascertained that Selam had attained only 65 to 88 percent of the adult brain size by the age of three. A chimp of comparable age, in contrast, has reached more than 90 percent of its adult brain size. This raises the tantalizing possibility that *A. afarensis* experienced a more humanlike pattern of brain growth.

More fossils are needed to discern whether the new skeleton is representative of *A. afarensis* infants, and scientists are doubtless eager to recover remains of other *A. afarensis* children of different ages—if they ever can—to see how they compare. But the little girl from Dikika still has more secrets to spill. "I think the impact of this specimen will be in its information of the growth and development of *Australopithecus*, not only for individual body parts but for rates of development among structures within one individual," observes Carol V. Ward of the University of Missouri–Columbia.

For his part, Alemseged estimates that it will take him several more years to finish removing the sandstone from Selam's bones. Once he does, however, he will be able to reconstruct nearly the entire body of an *A. afarensis* three-year-old—and begin to understand what growing up australopithecine was all about. SA

Kate Wong is editorial director of ScientificAmerican.com

MORE TO EXPLORE

New Look at Human Evolution. Special edition. *Scientific American,* Vol. 13, No. 2; 2003.

Becoming Human: Evolution and the Rise of Intelligence. Special edition. *Scientific American,* Vol. 16, No. 2; 2006.

Geological and Palaeontological Context of a Pliocene Juvenile Hominin at Dikika, Ethiopia. Jonathan G. Wynn et al. in *Nature,* Vol. 443, pages 332–336; September 21, 2006.

A Juvenile Early Hominin Skeleton from Dikika, Ethiopia. Zeresenay Alemseged et al. in *Nature,* Vol. 443, pages 296–301; September 21, 2006.

From Lucy to Language. Donald Johanson and Blake Edgar. Simon & Schuster, 2006.

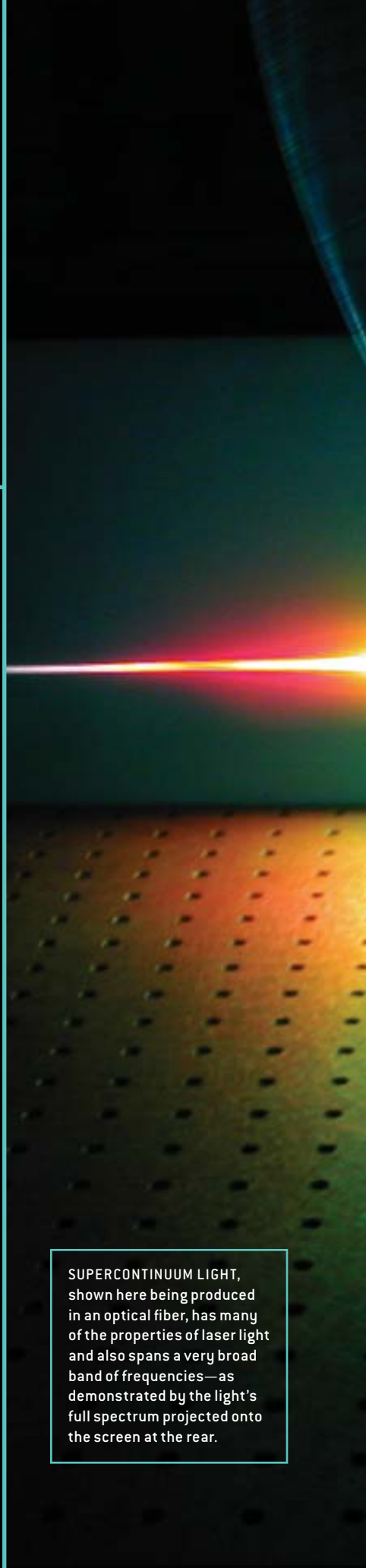
Extended coverage of *Lucy's Baby*—including more interviews, commentaries and photographs—can be found at ***www.sciam.com/ontheweb***

MELISSA THOMAS (*timeline*); AMERICAN MUSEUM OF NATURAL HISTORY, NEW YORK (*reconstruction*)

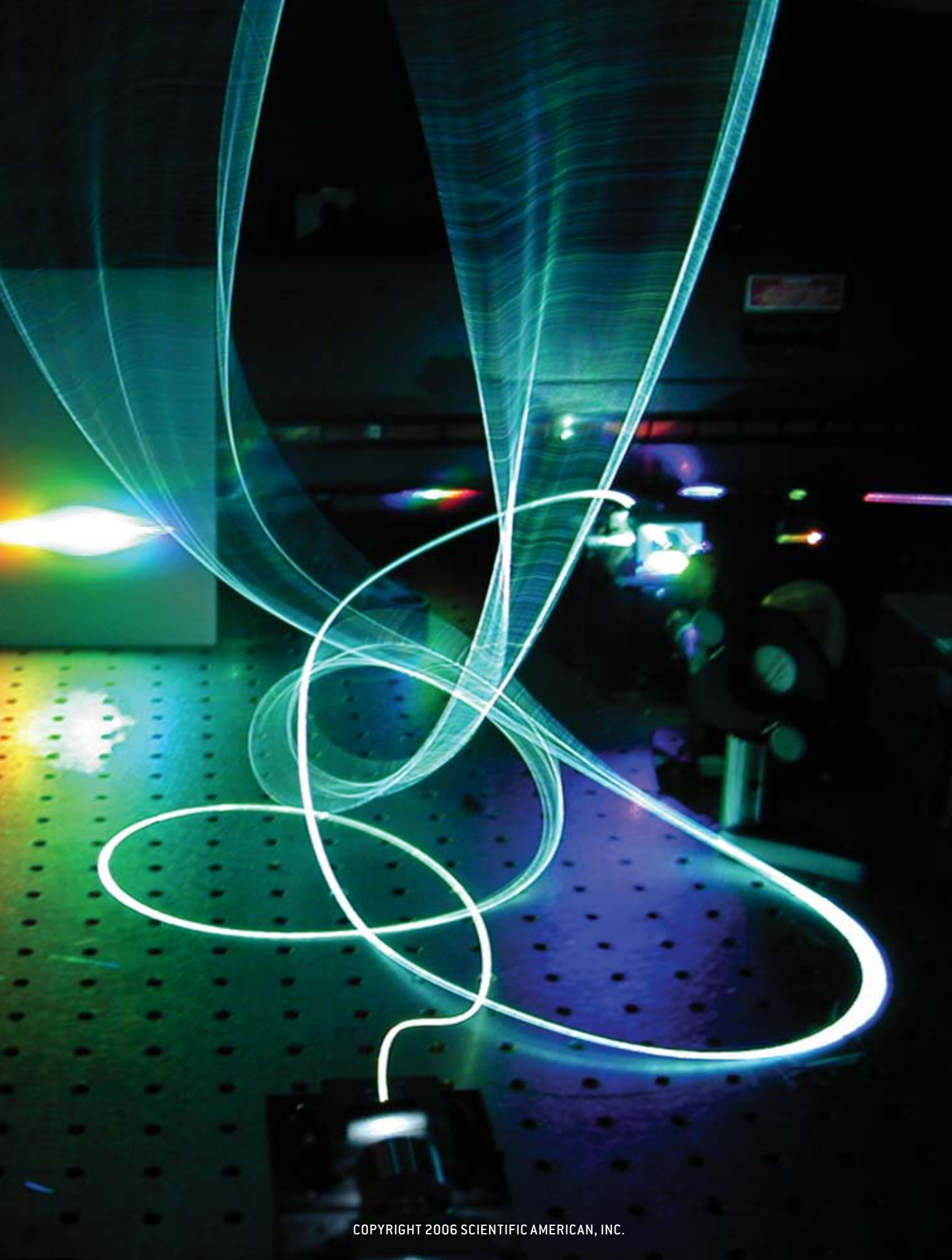
THE ULTIMATE WHITE LIGHT

By Robert R. Alfano

"Supercontinuum" laser light has enabled the most precise frequency and time measurements ever and might drive optical data transmission rates to record speeds



SUPERCONTINUUM LIGHT, shown here being produced in an optical fiber, has many of the properties of laser light and also spans a very broad band of frequencies—as demonstrated by the light's full spectrum projected onto the screen at the rear.



LIGHT IS ONE OF THE MOST IMPORTANT AND VERSATILE PHENOMENA IN NATURE.

Like a courier, it can transfer information from one point to another. Like an alchemist, it can alter matter. More specifically, it can initiate and moderate key processes in chemistry, biology and condensed matter. And of course, without it one could not see.

The versatility of light comes about because of the many forms it can take: brief flashes, focused spots, broad continuous beams, dim or intense light, polarized light, low- or high-frequency light, and light containing many frequencies at once. For visible light, the frequency determines the color and is related to the light's wavelength (shorter wavelengths correspond to higher frequencies). That most familiar of artificial light sources, an incandescent bulb, emits light across the full visible spectrum, resulting in white light.

If you want to do anything other than bathe a room in a warm glow, however, light from an incandescent bulb has several drawbacks: it is relatively low intensity, it is not collimated in a single direction and it is not coherent, meaning that the individual particles (photons) that make up the light do not oscillate in phase with one another. Lasers solve all three of those problems, but instead of emitting white light, a laser emits a narrow band of frequencies at best. For many applications, coherent light at a single frequency or a narrow band of frequencies is more than adequate. But having a light source that combines the properties of a laser with the broad bandwidth of an incandescent bulb opens up a whole new realm of possibilities.

In 1969, while I was pursuing my Ph.D. at New York University, I worked with Stanley L. Shapiro as a member of the technical staff at General Telephone and Electronics Laboratories (now Verizon) in Bayside, N.Y. Together we invented a new kind of laser light that spanned a large part of the visible spectrum, for which I coined the name "supercontinuum" (SC). Today researchers produce SC light that spans an entire octave or more. As with an octave of sound, an octave of light extends all the way from one frequency to double that frequency. The visible spectrum is approximately an octave, and thus the SC realizes the dream of white laser light.

A laser light that spans an octave enables certain very useful tricks. John L. Hall of the University of Colorado at Boulder and the National Institute of Standards and Technology there, along with Theodor W. Hänsch of the Max Planck Institute for Quantum Optics in Garching, Germany, received their share of the 2005 Nobel Prize in Physics for using such light to achieve extremely accurate time and frequency measurements.

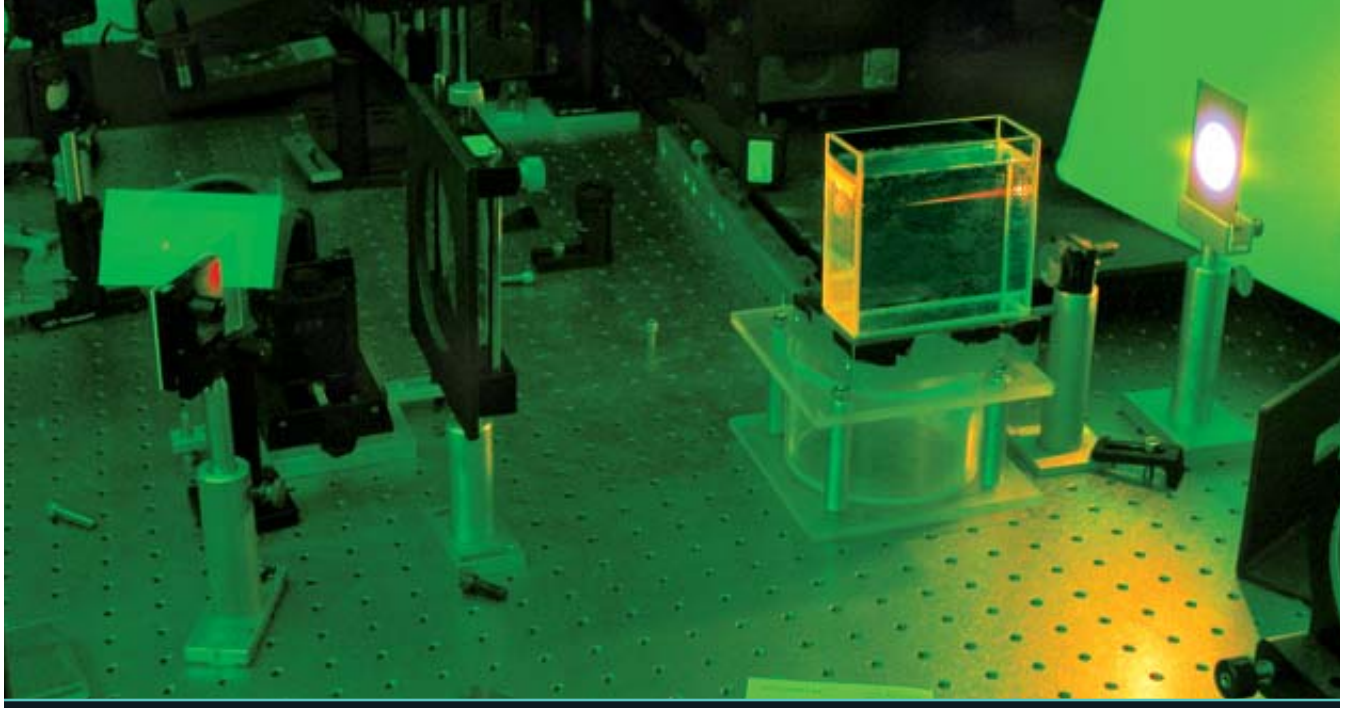
The basic technique that Shapiro and I used to produce the SC involved sending very high intensity pulses of green laser light that were only picoseconds long (trillionths of a second, or 10^{-12} second) through special crystals or glasses. I had been setting up to try to determine for the first time the lifetime of high-frequency vibrational excitations (phonons) in crystals such as calcite when I observed white light being generated. The light pulses had interacted with the medium in a way that broadened their bandwidth dramatically. Later, we also used liquids, and others used liquids and gases as the interaction medium to extend the SC spectrum further into the infrared.

The first application of the SC was to study the dynamics of vibrational excitations in liquids [see "Ultrafast Phenomena in Liquids and Solids," by R. R.

Overview/*Supercontinuum*

- Laser light is so useful because it has high intensity and a property known as coherence. Unlike white light, however, laser light usually contains only a narrow band of frequencies. "Supercontinuum" light combines the useful features of laser light with the broad bandwidth of white light.
- Today the favored method for producing supercontinuum light is to send high-intensity laser pulses through specially designed optical fibers. As the light travels down the fiber, it interacts with the fiber material by a number of so-called nonlinear optical processes that broaden its bandwidth.
- Applications for supercontinuum light include extremely accurate frequency and time measurements, high throughput telecommunications, detection of chemicals in the air, and medical imaging.

COURTESY OF JONATHAN KNIGHT *University of Bath (preceding pages)*



EXPERIMENTAL SETUP to produce supercontinuum light sends high-intensity laser light (*red*) through a suitable optical medium (here a container of liquid) that greatly broadens the light's bandwidth (*white light*).

Alfano and S. L. Shapiro; Scientific American, June 1973]. Soon thereafter investigators also used the SC as a novel tool to probe fundamental picosecond and femtosecond (10^{-15} second) processes. These included the primary chemical events that occur when photons of light are absorbed in photosynthesis and vision, the individual steps that make up chemical reactions, and the ways that molecules excited by light can relax without emitting light themselves.

In 1999 a new boom in SC research began when Jinendra K. Ranka, Robert S. Windeler and Andrew J. Stentz of Lucent Technologies generated an SC in a special kind of optical fiber. Among other advantages, the fiber confines the light to a small cross-sectional area, maintaining high intensities even as the light travels over long distances. (The nonlinear optical processes that the SC relies on become more pronounced at high intensities.) Researchers can also tailor the way that the optical properties of the fiber vary for different frequencies of light so that they optimize SC generation and exploit new physical effects in manipulating the light. As a result, today the SC has a plethora of applications, including extremely accurate time and frequency measurements, high-bandwidth optical communications, atmospheric science, an imaging technique called optical coherence tomography, the compression of ultrashort pulses to even shorter time spans, and perhaps spatial gravity measurements for oil and mineral detection.

Producing the Supercontinuum

Many different physical effects can contribute to the bandwidth broadening that results in SC pulses. The main one is a process known as self-phase modulation, in which the light modifies the material it is passing through in such a way that the altered material, in return, acts on the light to increase its bandwidth. To understand how this process works, consider the detailed waveform of a laser pulse: a graph of the electric field of the pulse would show a series of oscillations that start off small, grow to some maximum size and then diminish to nothing again [*see box on page 91*]. The general outline, or envelope, of the oscillations defines how the light's intensity steadily rises and then falls over the course of the pulse. How the oscillations travel through the medium depends on a property of the medium called the refractive index. The speed that light travels in a medium is the speed of light in a vacuum, c, divided by the refractive index.

Now, if the pulse has a sufficiently high intensity, the wave's electric field significantly distorts the electron clouds of the atoms making up the medium, increasing the material's refractive index at that location by a small amount. This phenomenon, called the optical Kerr effect, alters the phase of the pulse's oscillations, meaning that it alters the positions of the oscillations' peaks and troughs. Specifically, the increased index delays the peaks and troughs.

The amount by which the refractive index increases depends on the light's intensity, so as the pulse passes by a given location in the medium the refractive index there varies continuously, and so do the induced phase changes. In the front half of the pulse, the intensity and thus the refractive index are rising in time, so the relative positions of the peaks and troughs are increasingly delayed, which reduces the frequency of the wave. In the rear half, the index is falling in time and, correspondingly, the wave's frequency is increased.

When the pulse emerges from the medium, its oscillations are wider at the front of the pulse and narrower at the rear. Graphed, it looks somewhat like a spring stretched between two points with the middle of the spring pulled a short distance toward one end.

The broadening of the bandwidth becomes clearer when we consider the

COURTESY OF ROBERT R. ALFANO

spectrum of the pulse—the intensity of each frequency (or wavelength) that is present. Even before the optical Kerr effect comes into play, a pulse such as the one I have been describing does not consist of one pure frequency. Instead the pulse can be thought of as being made up of waves of many different frequencies added together. One property of any laser is that it produces light at specific discrete wavelengths. Consequently, a graph of the frequency spectrum of a laser pulse looks like a series of equally spaced spikes (a "frequency comb") in a pattern that has an envelope that forms another pulse shape. The width of this envelope defines the bandwidth or range of frequencies present. After an intense pulse travels through a medium where the Kerr effect is significant, the frequency envelope is wider.

In our 1969 discovery of the SC, Shapiro and I used picosecond pulses with an energy of a millijoule. A millijoule may sound like a low energy (it is the energy required to lift a paper clip several centimeters against the earth's gravity), but when it is packed into a picosecond and focused into a tight spot it represents a gigawatt of power and an extremely high intensity, capable of performing many tricks in that brief interval. Such a high intensity was necessary because the pulses could propagate through only a few centimeters of the glass where the Kerr effect was active. The high intensity could induce an effect strong enough to spread the pulses' bandwidth considerably even in the short time that they passed through the glass.

If the pulses traveled through more than a few centimeters of the glass, they started to come apart because of another property involving the refractive index called the dispersion of the medium.

DIFFRACTION, as occurs when a wave emerges from a small aperture, can influence supercontinuum generation. At the top, diffraction of a near-infrared laser beam through a 300-micron hole and onto a nearby glass slide produces a spot intense enough for supercontinuum generation (*white*). At the bottom, light diffracted by a straight edge generates supercontinuum light from two spots. The two beams interfere with each other, producing lines.

Dispersion in a normal medium means that the refractive index is slightly higher for higher-frequency light, which is therefore slowed down more than the lower-frequency light. Consequently, the different frequency components of the pulse travel at different speeds, and the pulse, whose existence depends on all the frequencies being tightly aligned ("in phase") at the center of the pulse, is quickly smeared out.

The optical fibers first used by Ranka and his colleagues in 1999 overcome this problem by having atypical dispersion properties, including zero dispersion and anomalous dispersion (meaning the refractive index decreases as the light frequency increases). With such fibers, SC pulses can propagate 1,000 times farther without coming apart. And because the pulses travel in the fiber for a much longer time, phenomena such as the Kerr effect have more time to operate and need not be as strong to have significant effects, which in turn means that the SC can be generated using lower-power lasers that emit microjoule and even nanojoule pulses instead of the millijoule pulses used earlier by researchers.

Another very important phenomenon plays a major role when the fiber has anomalous dispersion at the frequency band of the input pulse. In that situation, each pulse develops into a special kind of wave called a soliton. The characteristic property of a soliton is that it does not change its shape as it travels (usually a pulse tends to gradually spread out). This constancy arises because the anomalous dispersion acts on the soliton in a way that counterbalances the effects of other properties of the medium. When a material has anomalous dispersion, these solitons generate the SC rather than the self-phase modulation described earlier.

In either instance (normal or anomalous dispersion), the bandwidth of the SC is further broadened by a wide variety of other nonlinear optical effects, including four-wave mixing and Raman processes. In four-wave mixing, three frequencies of light interact in a nonlinear optical medium to generate light at a fourth frequency. Raman processes involve light interacting with the vibrational excitations of molecules making up the medium; as a result, the photons of light lose or gain energy, which changes their frequency.

All these interactions contribute simultaneously to greater or lesser degrees to the evolution of the pulses. Which processes dominate depends on all the factors that researchers can vary: the frequencies of light, the intensity

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ROBERT R. ALFANO is Distinguished Professor of Science and Engineering at the City College of the City University of New York, where he is director of the Institute for Ultrafast Spectroscopy and Lasers and the New York State Center for Advanced Technology in Photonics Applications. His research interests include biomedical imaging and spectroscopy, biophysics, ultrafast lasers, nonlinear optics and photonics. Alfano has published more than 700 papers in refereed journals and has 94 patents. He would like to thank Swapan Gayen, Alvin Halpern, Lauren Gohara, Kestutis Sutkus and Frances Rodriguez for their help with various aspects of the article.

and the time duration of the input pulses, and the optical properties of the fiber. A reliable way to predict the final result is to carry out numerical computer simulations of light pulses traveling through the fiber. Otherwise it is a matter of trying out the experiment and seeing what happens.

The fibers used for SC generation are a special kind known as microstructure fibers. A cross section of such a fiber reveals a pattern of holes that runs continuously through the entire length of the fiber [*see box on next page*]. In one commonly used design, the pattern of holes surrounds a solid silica core, like a honeycomb with only the central hole filled. The core has a high index of refraction, whereas the surrounding cladding, with its air holes interspersed with silica, has a lower index. That concentric arrangement of refractive indices serves to guide the light pulses along the fiber. Using these kinds of fibers with zero and anomalous dispersion, researchers have generated SC light extending more than two octaves from the infrared to the ultraviolet.

Metrology

AS MENTIONED EARLIER, the generation of SC light in optical fibers has unleashed a wide range of applications. The most important and mature of these applications is the development of extremely accurate frequency measurements and clocks. In this domain, the SC finds its usefulness in what are called optical frequency comb techniques, which enable improved accuracy with much simpler and smaller systems than the older methods. In particular, a trick called self-referencing, first demonstrated in 2000 independently by groups led by Hall and Hänsch, becomes possible when the frequency comb extends across a full octave. In this approach, scientists double the frequency of light at the low-frequency end of the spectrum and use it to interfere with light at the high-frequency end. [*Editors' note: A future article will discuss how self-referencing works in more detail.*]

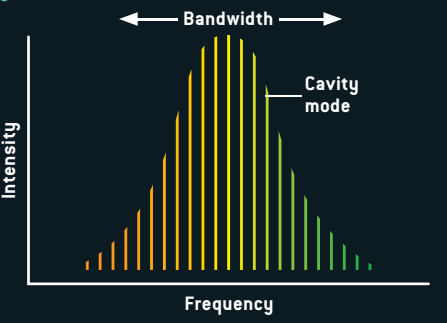
Building on Hall and Hänsch's work, scientists are now striving to develop

GENERATING SUPERCONTINUUM LIGHT

Pulsed lasers emit bursts of light with a limited range of frequencies. When a pulse of sufficiently high intensity passes through a medium such as an optical fiber, certain nonlinear processes occur, including one called self-phase modulation. These processes generate additional frequencies of light, creating the broad-spectrum supercontinuum output.

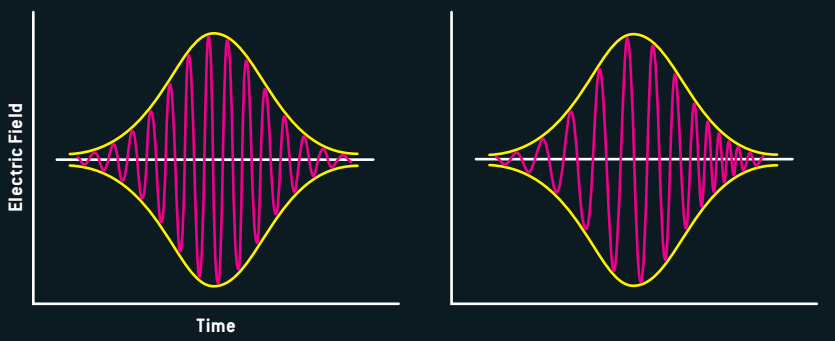
FREQUENCY COMB

Pulsed lasers emit a repeating series of pulses. Each pulse consists of many component beams and has a small range of frequencies. The spectrum of the series of pulses forms a frequency comb—an array of equally spaced discrete frequencies (cavity modes).



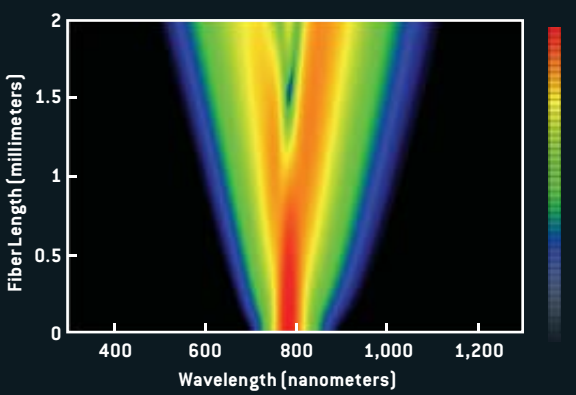
SELF-PHASE MODULATION

The electromagnetic oscillations of a laser pulse (*left, magenta*) have a constant wavelength but rise and fall in intensity (the envelope of the pulse, *yellow*). A pulse with high peak intensity can momentarily increase the medium's refractive index by an amount proportional to the intensity at each instant in time. As the medium's refractive index changes over time, it in turn modifies the wave's phase (the positions of the peaks and troughs, *right*), leading to new wavelengths and frequencies.



SPECTRAL BROADENING

A simulated 20-femtosecond (2×10^{-14} second) pulse traveling along an optical fiber reveals how nonlinear effects, including self-phase modulation, broaden the pulse's spectrum. Colors represent the intensity of light at each wavelength on a logarithmic scale (red is high intensity). In this example, after two millimeters of travel through the fiber, the light's spectrum spans just over an octave. (Like an octave in music, an octave of light spans from one frequency to double that frequency.)



MELISSA THOMAS (*top* and *middle*); RÜDIGER PASCHOTTA *RP Photonics Consulting* (*bottom*)

systems capable of measuring frequencies to a fractional accuracy of 10^{-16} to 10^{-18}. (The best achieved so far is about 10^{-14}.) Such extreme accuracy would have practical implications for improvements in Global Positioning Systems, space navigation, and the alignment of very large arrays of radio telescopes. It will also be put to use in tests of special relativity and related fundamental principles such as the isotropy of space, the symmetry of matter and antimatter, and the constancy of the constants of nature [see "The Search for Relativity Violations," by Alan Kostelecký; Scientific American, September 2004; "Making Cold Antimatter," by Graham P. Collins; Scientific American, June 2005; and "Inconstant Constants," by John D. Barrow and John K. Webb; Scientific American, June 2005].

Frequency measurements and clocks are two facets of the same technology. Researchers are currently pushing to develop clocks with an accuracy of a femtosecond (10^{-15} second) over a second. Ultimately, the optical frequency comb might enable fractional accuracies of 10^{-18}, which would be ideal for timing in optical computers and perhaps for detecting oil and mineral deposits by their minute effects on the nearby gravitational field.

Telecommunications

AN APPLICATION with more immediate commercial implications than ultraprecise frequency measurements is telecommunications. Indeed, several of the SC's key properties could make it an ideal basis for telecommunications systems capable of transmitting data more than 1,000 times faster than present-day systems. Optical fiber carrying infrared light is already the most widely used means of sending data at high rates over long distances. Scientists and engineers are working incessantly to cram ever more data into a fiber, in an effort to keep up with the ever increasing worldwide demand for larger-capacity communications systems and networks. The goal is to achieve transmission rates of terabits (10^{12}) and petabits (10^{15}) a second. Typical fiber-optic systems currently transmit data between cities at about 10 gigabits a second, or 0.01 terabit a second.

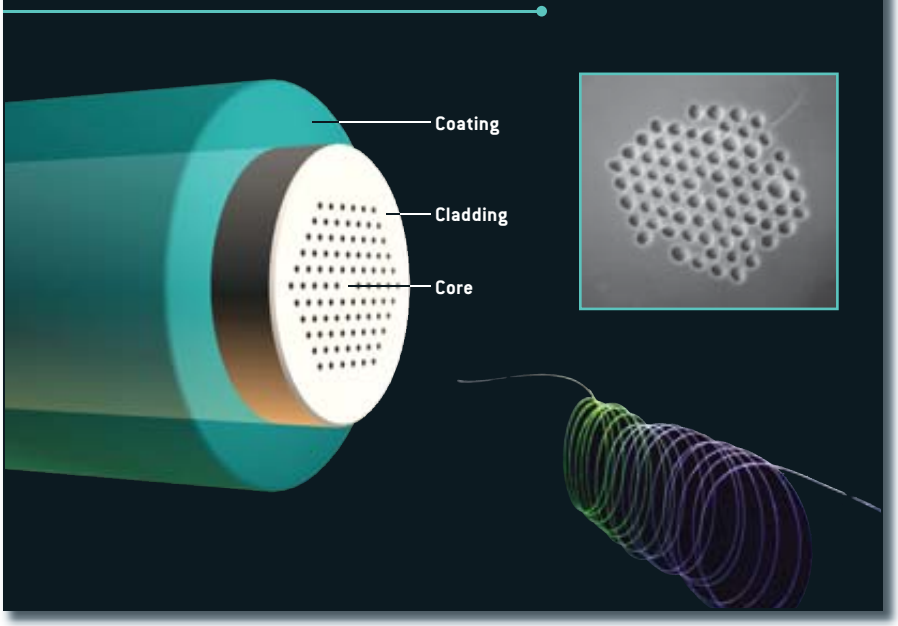
The ultrabroad bandwidth of the SC makes it a cost-effective way to obtain numerous wavelength channels without having to resort to using hundreds of lasers. That bandwidth could be put to work by the technique of superdense wavelength division multiplexing, in which data streams are encoded onto many different wavelengths of light that are transmitted simultaneously. The SC, unlike the light from 100 individual lasers, can be coherent across a wide range of frequencies (meaning that all the channels are oscillating in a kind of synchrony instead of each narrow band dancing to its own drummer), which aids in the degree of control that can be brought to bear on the light.

Alternatively, a series of ultrashort pulses of SC light (shorter than 100 femtoseconds, or 10^{-13} second) can be sent, with sequences representing different data channels interleaved with one another, a process called time-division multiplexing. With such short pulses, it is important to be able to control the precise relation between the individual oscillations of the electric field (the carrier wave) and the pulse envelope. This property, called the relative phase of the carrier and the envelope, determines, for example, whether the peak of the pulse envelope occurs at an instant when the electric field of the wave is at a peak or a trough, or somewhere in between. The properties of the SC facilitate such control.

Several Japanese groups have already achieved data transmission rates of terabits a second using a small segment of SC spectrum. Many challenges remain to be overcome to improve the speed to achieve petabit-a-second operation. These hurdles include reducing the duration of a bit to about a picosecond and increasing the number of coherent wavelengths in the SC.

MICROSTRUCTURED FIBERS

Optical fibers that have patterns of air holes running through them have revolutionized the generation and use of supercontinuum light. In one design (*below* and *top right*), the holes lower the index of refraction in the cladding that surrounds the small core of solid silica, a feature that confines light to the core. The changing color of light traveling along such a fiber (*bottom right*) reveals the bandwidth broadening that the fiber induces, which is enhanced by other properties of the fiber's refractive index.



MELISSA THOMAS (*illustration*); REPRINTED WITH PERMISSION OF LUCENT TECHNOLOGIES, INC./BELL LABS, COURTESY OF ANDREW STENTZ, JINENDRA RANKA AND R. S. WINDELER (*micrograph* and *spiral*)

Atmospheric Science

THE TELECOMMUNICATIONS applications rely on producing the SC in the completely controlled environment of an optical fiber, but for some purposes the SC is generated in the open air. One such purpose is remote sensing of molecular species present in air. When intense ultrafast laser pulses travel through the air, they can produce long, narrow "filaments" in which the air is ionized—that is, within those filaments electrons are knocked off the air's molecules, forming a plasma of positive ions and negatively charged electrons. These filaments can guide the light pulses and keep them from spreading, a process that scientists attribute to a balance between defocusing caused by diffraction (the tendency for a wave to spread out from a small aperture) and self-focusing caused by the ionized plasma.

Within the filaments a significant amount of the pulses' power can convert to SC white light over distances greater than 20 meters. Pollutants and aerosols in the air will absorb the light at characteristic frequencies, and the broad spectrum of the SC light enables one to detect their absorption spectra simultaneously in the ultraviolet, visible and infrared bands.

Imaging

IN ADDITION TO probing the air around us, SC light is useful for producing high-resolution images of the tissues inside us. The technique, optical coherence tomography (OCT), was pioneered by James G. Fujimoto of the Massachusetts Institute of Technology and his co-workers and can be carried out in situ in living organisms or on samples that have been removed. It has been used for studies of the retina, skin diseases, gastrointestinal diseases and carcinoma cells—in humans and in animals.

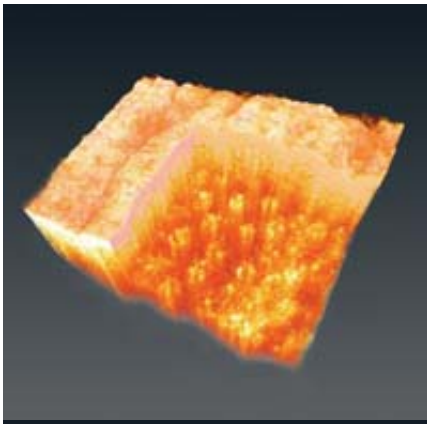
To produce an OCT image, the light is split into two parts—one part illuminates a spot of the sample, whereas the other ("reference" light) enters a length of fiber. When the reference light recombines with light that the sample reflected or scattered, the two interfere strongly—provided that they each spent the same length of time on their respective journeys. A property of the source light called its coherence length determines how accurately the timing has to match. High-resolution OCT imaging relies on a short coherence length, which requires the match to be very accurate.

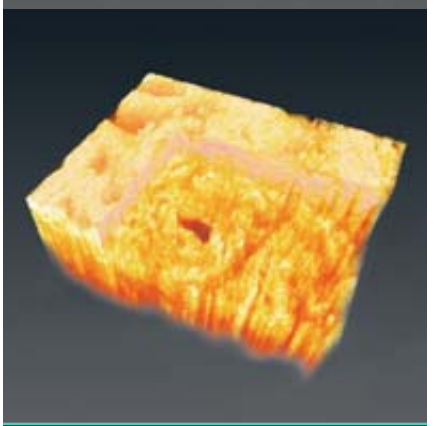
Thus, when the spot of light penetrates into the sample, only light coming back from one specific depth will interfere with the reference light. Scanning the light laterally across the sample while keeping the travel time of the reference light fixed therefore produces a two-dimensional image of the sample at a certain depth. The thickness of the layer that contributes to the image is called the axial resolution of the image.

Early OCT imaging systems relied on a type of diode to provide the light and had an axial resolution of 10 to 15 microns. (For comparison, high-frequency ultrasound images have a resolution of about 100 microns.) Femtosecond pulse lasers optimized to have short coherence lengths pushed the axial resolution to below two microns—nearly a 10-fold improvement.

The axial resolution also depends on the bandwidth of the light source—broader bandwidth enables finer resolution. SC light has a short coherence length and a bandwidth broader than any femtosecond laser, making it ideal for high-resolution OCT imaging. In 2002 Boris Považay, now at the Medical University of Vienna, and his co-workers used SC light generated in microstructured fibers to produce images of human carcinoma cells with an axial resolution of 0.5 micron (a typical cell is about 10 microns in diameter).

The supercontinuum is one of the most dramatic and elegant effects in optical physics: light of one color from an intense laser pulse passes through a crystal, optical fiber or a gas and turns white. But as well as being impressive to the naked eye, SC generation enables diverse applications, ranging from chemical sensing to the most precise time and frequency measurements available. The SC continues to grow to new heights of scientific activity 35 years after its discovery. SA





OPTICAL COHERENCE TOMOGRAPHY (OCT) uses light to produce images analogous to ultrasound but with much finer resolution. These three-dimensional OCT images of normal tissue (*top*) and a benign tumor (*bottom*), both from surgical specimens taken from the colon, reveal the disorganized glandular structure that is a signature of the latter. The use of supercontinuum light enabled resolution about four times finer than standard OCT images.

MORE TO EXPLORE

Observation of Self-Phase Modulation and Small-Scale Filaments in Crystals and Glasses. R. R. Alfano and S. L. Shapiro in *Physical Review Letters,* Vol. 24, No. 11, pages 592–594; March 16, 1970.

Supercontinuum Generation in Photonic Crystal Fiber. John M. Dudley, Goëry Genty and Stéphane Coen in *Reviews of Modern Physics,* Vol. 78, pages 1135–1184; October 4, 2006.

The Supercontinuum Laser Source: Fundamentals with Updated References. Edited by Robert R. Alfano. Springer, 2006.

Encyclopedia of Laser Physics and Technology. Rüdiger Paschotta. Online at **www.rp-photonics.com/encyclopedia.html**

CANCER Clues from

Studies of pet dogs with cancer can offer unique help in the fight against human malignancies while also improving care for man's best friend

Imagine a 60-year-old man recuperating at home after prostate cancer surgery, drawing comfort from the aged golden retriever beside him. This man might know that a few years ago the director of the National Cancer Institute issued a challenge to cancer researchers, urging them to find ways to "eliminate the suffering and death caused by cancer by 2015." What he probably does not realize, though, is that the pet at his side could be an important player in that effort.

Reaching the ambitious Cancer 2015 goal will require the application of everything in investigators' tool kits, including an openness to new ideas. Despite an unprecedented surge in researchers' understanding of what cancer cells can do, the translation of this knowledge into saving lives has been unacceptably slow. Investigators have discovered many drugs that cure artificially induced cancers in rodents, but when the substances move into human trials, they usually have rough sledding. The rodent models called on to mimic human cancers are just not

PET DOGS

By David J. Waters and Kathleen Wildasin

DOGS AND HUMANS often fall ill with the same kinds of cancers. Scientists contend that the similarities between these tumors, including genetic resemblances, can be instructive. (The background represents the DNA sequence from a tissue sample.)

measuring up. If we are going to beat cancer, we need a new path to progress.

Now consider these facts. More than a third of American households include dogs, and scientists estimate that some four million of these animals will be diagnosed with cancer this year. Pet dogs and humans are the only two species that naturally develop lethal prostate cancers. The type of breast cancer that affects pet dogs spreads preferentially to bones—just as it does in women. And the most frequent bone cancer of pet dogs, osteosarcoma, is the same cancer that strikes teenagers.

Researchers in the emerging field of comparative oncology believe such similarities offer a novel approach for combating the cancer problem. These investigators compare naturally occurring cancers in animals and people—exploring their striking resemblances as well as their notable differences.

Right now comparative oncologists are enlisting pet dogs to tackle the very obstacles that stand in the way of achieving the Cancer 2015 goal. Among the issues on their minds are finding better treatments, deciding which doses of medicines will work best, identifying environmental factors that trigger cancer development, understanding why some individuals are resistant to malignancies and figuring out how to prevent cancer. As the Cancer 2015 clock keeps ticking, comparative oncologists ask, Why not transform the cancer toll in pet dogs from something that is only a sorrow today into a national resource, both for helping other pets and for aiding people?

Why Rover?

FOR DECADES, scientists have tested the toxicity of new cancer agents on laboratory beagles before studying the compounds in humans. Comparative oncologists have good reason to think that pet dogs with naturally occurring cancers can likewise become good models for testing the antitumor punch delivered by promising treatments.

One reason has to do with the way human trials are conducted. Because of the need to ensure that the potential benefits of an experimental therapy outweigh the risks, researchers end up evaluating drugs with the deck stacked against success; they attempt to thrash bulky, advanced cancers that have failed previous treatment with other agents. In contrast, comparative oncologists can test new treatment ideas against early-stage cancers—delivering the drugs just as they would ultimately be used in people. When experimental drugs prove helpful in pets, researchers gain a leg up on knowing which therapies are most likely to aid human patients. So comparative oncologists are optimistic that their findings in dogs will be more predictive than rodent studies have been and will help expeditiously identify those agents that should (and should not) be tested in large-scale human trials.

Pet dogs can reveal much about human cancers in part because of the animals' tendency to become afflicted with the same types of malignancies that affect people. Examples abound. The most frequently diagnosed form of lymphoma affecting dogs mimics the medium- and high-grade B cell non-Hodgkin's lymphomas in people. Osteosarcoma, the most common bone cancer of large- and giant-breed dogs, closely resembles the osteosarcoma in teenagers in its skeletal location and aggressiveness. Under a microscope, cancer cells from a teenager with osteosarcoma are indistinguishable from a golden retriever's bone cancer cells. Bladder cancer, melanoma and mouth cancer are other examples plaguing both dog and master. In a different kind of similarity, female dogs spayed before puberty are less prone to breast cancer than are their nonspayed counterparts, much as women who have their ovaries removed, who begin to menstruate late or who go into menopause early have a reduced risk for breast cancer.

Canine cancers also mimic those of humans in another attribute—metastasis, the often life-threatening spread of cancer cells to distant sites throughout the body. Solving the mystery of how tumor cells metastasize to particular organs is a top research priority. When certain types of cancers spread to distant organs, they tend to go preferentially to some tissues over others, for reasons that are not entirely clear. Because metastasis is what accounts for most deaths from cancer, researchers would very much like to gain a better understanding of its controls. Studies in pet dogs with prostate or breast cancer might prove particularly useful in this effort, because such tumors frequently spread in dogs as they do in humans—to the skeleton. Indeed, research in pet dogs is already attempting to work out the interactions between tumor cells and bone that make the skeleton such a favorite site for colonization.

Scientists also have deeper theoretical grounds for thinking that pet dogs are reasonable models for human cancer. Evolutionary biologists note that dogs and humans are built like Indy race cars, with successful reproduction as the finish line. We are designed to win the race, but afterward it does

Overview/*Canine Cancer*

- Millions of pet dogs will have cancer diagnosed this year. In many of those animals, the malignancy will look and behave much as it would in humans, such as spreading to the same organs.
- Investigation of these cancers can help researchers to better understand the biology of the human forms. Also, studies of experimental treatments in the animals can indicate which therapies most deserve further testing in dogs and humans and can offer guidance on the best doses and methods of delivery.
- Such studies should improve cancer prevention and therapy for both humans and their canine companions.

ALISON KENDALL (*illustration*); PASIEKA *Photo Researchers, Inc.* (*autoradiogram*) (*preceding pages*); JANA BRENNING (*this page*)

BREEDS AT RISK

The breeds represented by the dogs shown here are particularly susceptible to cancers that also afflict humans. These malignancies look like the human forms under a microscope and act similarly as well. Such resemblances mean that canine responses to experimental drugs should offer a good indication of how the compounds will work in humans. In addition, research into the genes that increase susceptibility of specific breeds to particular cancers is expected to help pinpoint susceptibility genes in humans.

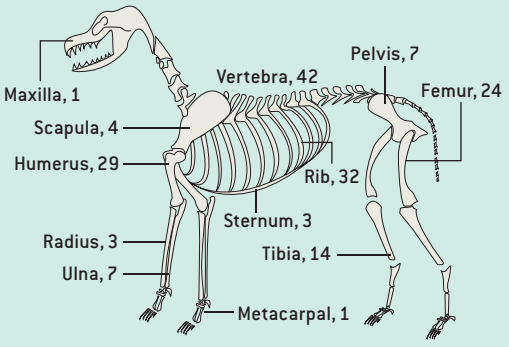
Rottweiler:
Bone cancer

Collie:
Nasal cancer

Chow Chow:
Stomach cancer

Golden Retriever:
Lymphoma

Boxer:
Brain cancer



SKELETAL DISTRIBUTION of metastases is another aspect of cancer similar in dogs and humans. In dogs, the lesions display the same "above the elbow, above the knee" pattern seen in people. Insights into why that pattern occurs in dogs could help explain the distribution in humans and perhaps suggest new ideas for intervening. (The numerals indicate the number of metastases found at each site in one study.)

Scottish Terrier:
Bladder cancer

DK LTD. *Corbis (retriever)*; CORBIS *(rottweiler)*; CORBIS *(boxer)*; YANN ARTHUS-BERTRAND *Corbis (chow chow, terrier, collie)*; DANIELA NAOMI MOLNAR, SOURCE: DAVID WATERS *(dog skeleton)*

not matter how rapidly we fall apart. This design makes us ill equipped to resist or repair the genetic damage that accumulates in our bodies. Eventually this damage can derange cells enough to result in cancer. In the distant past, our human ancestors did not routinely live long enough to become afflicted with age-related cancers. But modern sanitation and medicine have rendered both longevity and cancer in old age common. Much the same is true for our pets. Pet dogs, whom we carefully protect from predation and disease, live longer than their wild ancestors did and so become prone to cancer in their later years. Thus, when it comes to a high lifetime risk for cancer, pets and people are very much in the same boat.

Aside from acquiring cancers that resemble those in people, pet dogs are valuable informants for other reasons. Compared with humans, they have compressed life spans, so scientists can more quickly determine whether a new prevention strategy or therapy has a good chance of improving human survival rates. Finally, although veterinarians today are far better equipped to treat cancer than they used to be, the standard treatments for many canine tumors remain ineffective. Because most pet cancer diagnoses end in death, dog owners are often eager to enroll their animals in clinical trials that could save their pet's life—and possibly provide the necessary evidence to move a promising therapy to human clinical trials.

Advancing Cancer Therapy

VARIOUS CANCER TREATMENT studies featuring pet dogs have now been carried out or begun. Some of the earliest work focused on saving the limbs of teenagers with bone cancer. Twenty-five years ago a diagnosis of osteosarcoma in a youngster meant amputation of the affected limb, ineffective or no chemotherapy (drugs administered into the bloodstream to attack tumors anywhere in the body), and almost certain death. Today limb amputation can be avoided by chiseling out the diseased bone tissue and replacing it with a bone graft and metal implant—a process partially perfected in pet dogs by Stephen Withrow and his colleagues at Colorado State University. Withrow's team pioneered technical advances that reduced the likelihood of complications, such as placing bone cement in the marrow space of the bone graft. The researchers also showed that preoperative chemotherapy delivered directly into an artery could convert an inoperable tumor into an operable one. The group's work is credited with significantly increasing the percentage of teenagers who today can be cured of osteosarcoma.

Although a tumor's local effects are often controllable using surgery or radiation, metastasis is much harder to combat. For that, drug therapy is required. New compounds under development aim to disrupt key cellular events that regulate the survival and proliferation of metastatic tumor deposits as well as their sensitivity to cancer-fighting drugs. One experimental agent, ATN-161, which inhibits the formation of new blood vessels that foster tumor growth and metastasis, is currently being evaluated in large-breed dogs with bone cancers that have spread to the lungs. The ability of ATN-161 to enhance the effects of conventional chemotherapies is also under study. If these trials succeed, they could smooth the way toward clinical trials in humans.

Cancer researchers are also turning their attention to more familiar kinds of pharmaceuticals, including nonsteroidal anti-inflammatory drugs (NSAIDs), the class of compounds that includes ibuprofen. Certain NSAIDs have exhibited significant antitumor activity against a variety of canine tumors. In studies of pet dogs with bladder cancer, for example, the NSAID piroxicam showed such impressive antitumor activity that the drug is now in human clinical trials to see if this treat-

The Ideal Animal Model: An Invalid Concept

RODENTS are a favorite model of cancer researchers, but therapies that work beautifully in rats and mice often fail in humans.

Some experts contend that progress toward finding cancer cures has been frustratingly slow because of the inadequacy of available animal models of human cancer. But perhaps the problem is not in the animals themselves but in the way they are used and what we are forcing them to tell us.

The dictionary defines a model as "an imitation." By definition, therefore, an animal model of cancer is not the same as a person who acquires cancer. Rodent models are often produced by making "instant cancers"—that is, by injecting the animals with tumor cells or bombarding them with carcinogen doses that are higher than any human will ever encounter. It is doubtful that cancers produced in that way will accurately recapitulate a complex process that often requires more than 20 to 30 years to develop in people. Naturally occurring animal tumors, such as those affecting pet dogs, provide the opportunity to study this complexity in a less artificial way.

But no one animal model is capable of answering all the important questions related to the prevention or treatment of a particular type of human cancer. Researchers would be best served by turning their attention toward carefully crafting specific questions and letting the questions drive the selection of the model system. For some questions, cell culture or rodent studies will be appropriate. To answer others, researchers will have to resort to studying humans. In that sense, a human clinical trial is a form of animal model research—a specific collection of people is being used to represent the overall human population. *—D.J.W.*

PASCAL GOETGHELUCK *Photo Researchers, Inc.*

ment can derail the progression of precancerous bladder lesions to life-threatening cancer.

Developing new cancer therapies is not just about finding novel drugs. It is about optimizing drug delivery to the patient. In your vein or up your nose? That is the kind of information scientists testing new agents against lung cancer need to know. If the right amount of drug does not make it to the tumor, then even substances with impressive credentials for killing tumor cells in a petri dish will not stand a chance of working in human patients. Moreover, delivering pharmaceuticals directly to the target—so-called regional therapy—has the added benefit of avoiding the toxicity associated with systemic therapy.

Investigators have used pet dogs to study the intranasal delivery of a cytokine, a small immune system molecule, called interleukin-2 (IL-2) to treat naturally occurring lung cancers. Positive results from these experiments led to feasibility trials of inhaled IL-2 in human patients with lung metastases, further leading to trials with another cytokine, granulocyte colony stimulating factor. Pet dogs can also aid researchers in optimizing the dosing and delivery protocols for drugs that have already made their way into human trials.

Another challenge that pet dogs are helping to overcome is determining the extent of tumor spread, called clinical staging. Accurate staging is critical for devising therapeutic game plans that will maximally benefit the patient while minimizing exposure to harsh treatments that are unlikely to help at a given disease stage. For example, the odds that a teenager will survive osteosarcoma are increased by accurate identification (and subsequent surgical removal) of lung metastases.

Doctors typically determine the presence and extent of such metastases with noninvasive imaging techniques, such as computed tomography (CT). To assess how accurate such scanning is, one of us (Waters), along with investigators from Indiana University School of Medicine, collected CT images of the lungs from pet dogs with metastatic bone cancer and then examined the tissue at autopsy to verify that what was interpreted as a "tumor" on the scan really was a tumor and not a mistake. Results showed that state-of-the-art imaging with CT—the same type used in clinical staging of bone cancer in teenagers—significantly underestimates the number of cancer deposits within the lung. By revealing the limited accuracy of existing and experimental techniques, pet dogs are helping optimize the next generation of technologies for improved cancer detection.

Taking Aim at Cancer Prevention

BUT CANCER RESEARCHERS are shooting for more than improved detection and better treatment; they also want to prevent the disease. Surprisingly, prevention is a relatively new concept within the cancer research community. What cardiologists have known for a long time—that millions of lives can be saved through the prevention of heart disease—is just now gaining traction in the cancer field. The term "chemoprevention" was coined 30 years ago to refer to the administration of compounds to prevent cancer, but scientists did not gather nationally to debate cutting-edge knowledge of cancer prevention until October 2002.

Today the pace is quickening as investigators are examining a diverse armamentarium of potential cancer-protective agents. But finding the proper dose of promising agents has always been challenging. Indeed, failure to do so proved disastrous for some early human trials of preventives. For example, in two large lung cancer prevention trials, people receiving high doses of the antioxidant nutrient beta-carotene had an unexpected *increase* in lung cancer incidence compared with placebo-treated control subjects.

Can dogs accelerate progress in cancer prevention? Recently canine studies have helped define the dose of an antioxidant—the trace mineral selenium—that minimizes cancer-causing genetic damage within the aging prostate. The message from the dogs: when it comes to taking dietary supplements such as selenium to reduce your cancer risk, more of a good thing is not necessarily better. Elderly dogs given moderate doses ended up with less DNA damage in their prostates than dogs given lower or higher amounts. Comparative oncologists hold that dog studies conducted before large-scale human prevention trials are initiated can streamline the process of finding the most effective dose of cancer preventives and can enable oncologists to lob a well-aimed grenade at the cancer foe.

Pet dogs can assist in preventing human cancers in another way. For years, dogs in the research laboratory have advanced understanding of the acute and long-term effects of high doses of cancer-causing chemicals. But pet dogs, just by going about their daily lives, could serve as sentinels—watchdogs, if you will—to identify substances in our homes and in our backyards that are carcinogenic at lower doses. If something can cause cancer, the disease will show up in pets,

THE AUTHORS

DAVID J. WATERS and *KATHLEEN WILDASIN* share an interest in stimulating fresh thinking about cancer. Waters is professor of comparative oncology at Purdue University, associate director of the Purdue Center on Aging and the Life Course and executive director of the Gerald P. Murphy Cancer Foundation in West Lafayette, Ind. He earned his B.S. and D.V.M. at Cornell University and a Ph.D. in veterinary surgery at the University of Minnesota. Wildasin is a Kentucky-based medical and science writer.

JANA BRENNING

with their compressed life spans, well before it will in people.

Take asbestos. Most human cases of mesothelioma (a malignancy of tissues lining the chest and abdomen) stem from asbestos exposure. Symptoms can appear up to 30 years after the incriminating exposure. Investigators have now documented that mesothelioma in pet dogs is also largely related to encountering asbestos, most likely through being near a master who came into contact with it through a hobby or work. But in dogs, the time between exposure and diagnosis is comparatively brief—less than eight years. So the appearance of the cancer in a dog can alert people to look for and remediate any remaining sources of asbestos. Also, closer monitoring of exposed individuals might lead to earlier diagnosis of mesothelioma and render these cancers curable.

Pet dogs could assist in discovering other environmental hazards. Some well-documented geographic "hot spots" show an unusually high incidence of certain cancers. For example, women living in Marin County, California, have the country's highest breast cancer rate. Scientists typically try to identify the factors contributing to cancer in hot spots by comparing the genetics and behavior of people who become afflicted and those who do not. To advance the effort, comparative oncologists are now establishing cancer registries for pet dogs in those areas. If both pets and people living in a particular community experience higher-than-normal cancer rates, the finding would strengthen suspicions that these malignancies are being triggered by something in the environment.

Analyzing tissues of dogs could even potentially speed identification of the specific hazard. Many toxic chemicals, such as pesticides, concentrate themselves in body fat. So it might make sense to collect tissues from dogs during common elective surgical procedures (for example, spaying) or at autopsy. Later, if an unusually high number of people in an area acquire a certain form of cancer, investigators could analyze levels of different chemicals in the samples to see if any are particularly prominent and worth exploring as a contributing factor.

Why Uncle Bill Avoided Cancer

BECAUSE CANCER IN PET DOGS is so commonplace, the animals might be able to assist in solving an age-old mystery.

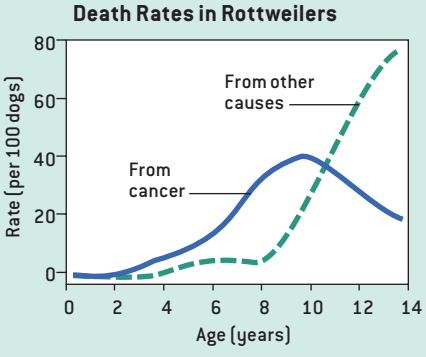
Cancer Resistance: Lessons from the Oldest Old


Anvil at age 13

The risk of most human and canine cancers increases dramatically with age. This pattern has led to the belief that cancer is simply the result of a time-related accumulation of genetic damage. But recent studies of people who live to be 100 years old (centenarians) reveal an intriguing paradox: the oldest old among us are much less likely to succumb to cancer than are people who die in their 70s or 80s. Do the oldest-old pet dogs share a similar resistance to cancer mortality?

To answer this question, my colleagues and I consulted pet owners and veterinarians to construct lifetime medical histories of a large cohort of rottweiler dogs living in North America. We found that the likelihood of dying from cancer within two years rose with age during adulthood until dogs reached about 10 years but then declined after that. Moreover, exceptionally old dogs (those older than 13 years) were much less likely to die of cancer than were dogs with usual longevity even though the risk of dying from other causes continued to rise.

These findings raise the exciting possibility that studies comparing oldest-old dogs to those with usual longevity might reveal genes that regulate cancer resistance. Gene variations (so-called polymorphisms) responsible for cancer resistance and exceptional longevity in dogs could then be evaluated to see whether they are also overrepresented in the oldest-old humans. If they are, scientists can try to learn how the molecular interactions regulated by these genes alter cancer susceptibility at the tissue level.



IN ROTTWEILERS who live past 10 years, getting older means having better odds of avoiding death from cancer.


Grace Fair at age 103

At present, the precise nature of cancer resistance in human centenarians is poorly defined. Detailed autopsy studies of oldest-old dogs are currently under way to explore this issue. These studies should determine whether cancer resistance reflects a complete suppression of the biological events that give rise to cancer—for example, through increased repair of DNA damage—or whether tumors actually arise but are of the nonlife-threatening variety. By better understanding the genetic and pathological basis of cancer resistance in the oldest old, scientists will be better positioned to develop practical interventions that will reduce the average person's cancer risk. —*D.J.W.*

COURTESY OF DONNA RICE (*rottweiler*); COURTESY OF THE NEW ENGLAND CENTENARIAN SOCIETY (*woman*)

Almost everyone has an Uncle Bill who smoked two packs a day and never got lung cancer. So what factors determine cancer resistance? One way to tease out the answer is to find populations resistant to cancer and study them closely—their genetics, their diet and their lifestyle.

Such a population has been found—human centenarians. It turns out that most folks who live to be 100 die of disorders other than cancer. But it is nearly impossible to collect reliable information from a 102-year-old woman on her dietary habits and physical activity when she was a teenager or in her mid-40s. So one of us (Waters) asked a simple question: Is this phenomenon of cancer resistance in the oldest old operational in pet dogs? The answer is yes [*see box on opposite page*]. Now by interviewing owners of very old pet dogs, comparative oncologists can construct accurate lifetime histories of "centenarian" dogs. Combine this prospect with the ability to collect biological samples (such as blood for genetic analysis and for tests of organ function) from very old dogs as well as from several generations of their offspring, and you have a unique field laboratory for probing the genetic and environmental determinants of cancer resistance.

The puzzle of cancer resistance can also be addressed in another way—by examining differences in cancer susceptibility between dogs and humans. In people, obesity and diets rich in animal fat are known to increase risk for colon cancer. In contrast, colorectal cancer in dogs is uncommon, even though many pet dogs are obese and consume a high-fat diet. Scientists are now contemplating the use of dogs as a "negative model" of colon cancer in the hope of identifying factors able to confer cancer resistance to people whose style of living strongly favors colon cancer development. Knowledge of resistance factors could suggest new interventions for nonresistant individuals.

A Growing Effort

HISTORICALLY, comparative oncology research has been conducted in university-based hospitals and laboratories where veterinary oncologists are trained. But other organizations have begun to recognize the potential for this kind of research to translate into better care for people, and these institutions are now actively engaged in comparative oncology research.

The Gerald P. Murphy Cancer Foundation began in 2001 to accelerate the discovery of improved methods for preventing and treating prostate and bone cancers affecting both people and pets. The Animal Cancer Foundation in New York City has funded comparative oncology studies and has recently established a repository of biological specimens of diseased and healthy animals as a resource for researchers chasing biological indicators of cancer risk. And in 2003 the National Cancer Institute developed the Comparative Oncology Program, which designs trials involving dogs with naturally occurring cancers and also provides researchers with high-quality, canine-specific reagents needed for in-depth studies of the molecular biology, protein chemistry and genetics of dog tumors.

Moreover, the sequencing of the canine genome is now complete. Discovery that a particular gene is involved in some form of cancer in dogs will enable investigators to determine whether—and how—the same gene operates in human cancers. Scottish terriers with bladder cancer, rottweilers with bone cancer and golden retrievers with lymphoma—each breed can help elucidate the calamitous combinations of genes and environment that lead to cancer.

Of course, there are limitations inherent in the use of animals to mimic human cancer—whether you are talking about rodents, dogs or other species. No single, ideal animal model for cancer exists [*see box on page 98*]. The best science is done by asking good questions and then using the research tools most likely to yield meaningful answers. At times, following that rule in cancer research will mean turning to dogs to track down that hard-to-win knowledge.

The intriguing similarities between the cancers of people and pets—once a mere curiosity—are now being systematically applied to transform cancer from killer to survivable nuisance. Comparative oncologists are not inducing cancer in animals but are compassionately treating pet dogs suffering from the same kinds of lethal cancers that develop naturally in both man and man's best friend. They are putting our canine companions on the trail of a killer in ways that can save both pets and people. SA

MORE TO EXPLORE

Exceptional Longevity in Pet Dogs Is Accompanied by Cancer Resistance and Delayed Onset of Major Diseases. D. M. Cooley, D. L. Schlittler, L. T. Glickman, M. Hayek and D. J. Waters in *Journal of Gerontology,* Vol. 58, No. 12, pages B1078–B1084; 2003.

Phase I Dose-Escalating Study of SU11654, a Small Molecule Receptor Tyrosine Kinase Inhibitor, in Dogs with Spontaneous Malignancies. C. A. London et al. in *Clinical Cancer Research,* Vol. 9, pages 2755–2768; 2003.

Herbicide Exposure and the Risk of Transitional Cell Carcinoma of the Urinary Bladder in Scottish Terriers. L. T. Glickman, M. Raghavan, D. W. Knapp, P. L. Bonney and M. H. Dawson in *Journal of the American Veterinary Medical Association,* Vol. 224, No. 8, pages 1290–1297; 2004.

Spontaneous and Genetically Engineered Animal Models: Use in Preclinical Cancer Drug Development. K. Hansen and C. Khanna in *European Journal of Cancer,* Vol. 40, pages 858–880; 2004.

Comparative Oncology Program of the National Cancer Institute (including information about clinical trials for dogs): **http://ccr.cancer.gov/resources/cop/**

JANA BRENNING

Weighty Matters

THE CENTURY-OLD ARTIFACT THAT DEFINES THE KILOGRAM, THE FUNDAMENTAL UNIT OF MASS, IS TO BE REPLACED BY A MORE ACCURATE STANDARD BASED ON AN INVARIANT PROPERTY OF NATURE

BY IAN ROBINSON

In an age when technologies typically grow obsolete in a few years, it is ironic that almost all the world's measurements of mass (and related phenomena such as energy) depend on a 117-year-old object stored in the vaults of a small laboratory outside Paris, the International Bureau of Weights and Measures. According to the International System of Units (SI), often referred to as the metric system, the kilogram is equal to the mass of this "international prototype of the kilogram" (or IPK)—a precision-fabricated cylinder of platinum-iridium alloy that stands 39 millimeters high and is the same in diameter.

The SI is administered by the General Conference on Weights and Measures and the International Committee for Weights and Measures. During the past several decades the conference has redefined other base SI units (those set by convention and from which all other quantities are derived) to vastly improve their accuracy and thus keep them in step with the advancement of scientific and technological understanding. The standards for the meter and the second, for example, are now founded on natural phenomena. The meter is tied to the speed of light, whereas the second has been related to the frequency of microwaves emitted by a specific element during a certain transition between energy states.

Today the kilogram is the last remaining SI unit still based on a unique man-made object. Reliance on such an artifact poses problems for science as measurement techniques become more precise. Metrologists (specialists in measurement) are therefore striving to define mass using techniques depending only on unchanging properties of nature. Two approaches seem most promising—one based on the concept underlying the Avogadro con-

METAL CYLINDER (*right*), weighing one kilogram, is the precision-manufactured mass standard used to calibrate all the mass scales in Italy. Like all other national mass standards worldwide, it is itself calibrated against an identical master artifact in France.

FROM A SILICON SPHERE TO A KILOGRAM STANDARD

One approach to redefining the kilogram is based on accurately quantifying the number of atoms in a silicon sphere weighing one kilogram.

1 The method starts with native silicon (a mixture of three isotopes—^{28}Si, ^{29}Si and ^{30}Si), which is reacted with fluorine to create gaseous silicon fluoride (SiF_4).

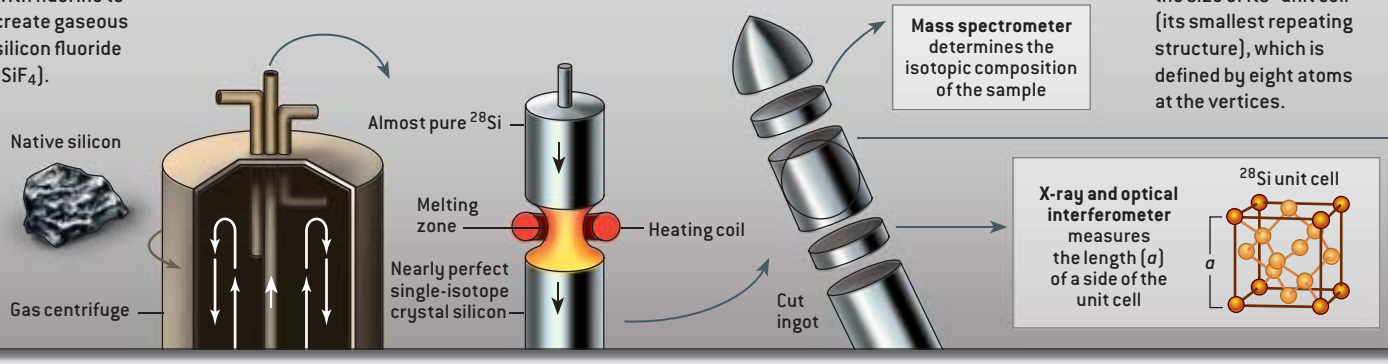
2 Researchers place the SiF_4 in centrifuges, which spin rapidly to separate the lightest isotope, ^{28}Si, from the others.

3 The resulting solidified material has a ^{28}Si concentration of around 99.99 percent. Workers then melt the refined silicon and make an ingot of nearly perfect crystalline silicon.

4 They next slice the recrystallized ingot into a large cylindrical work piece and several smaller samples for analysis.

5 Researchers place one sample in a mass spectrometer to ascertain the material's purity and thus its average molar mass (m), its mass per mole.

6 The other sample is analyzed using interferometry to measure the distance between the crystal's atomic planes. From this length, researchers find the size of its "unit cell" (its smallest repeating structure), which is defined by eight atoms at the vertices.



stant, the number of atoms in 12 grams of carbon 12, and the other involving Planck's constant, the fundamental value physicists use, for example, to calculate a photon's energy from its frequency. Because scientists measure constants in SI units (including the kilogram), any drift in the IPK's real mass will give rise to a drift in the value of a measured constant—a seeming paradox for what is commonly considered an immutable phenomenon. In the process of more accurately redefining the kilogram independently of the IPK, however, scientists will choose a best estimate of the constant's value and thus "fix" it.

Web of Measurements

THE PRESENT DEFINITION of the kilogram requires that all SI mass measurements carried out in the world be related to the mass of the IPK. ("Mass" is commonly equated with "weight," but technically the "mass" of an object refers to the amount of matter in it, whereas its "weight" is caused by the gravitational attraction between the object and the earth.) To forge this link, metrologists remove the IPK from its sanctuary every 40 years or so to calibrate the copies of the IPK that are sent to the International Bureau of Weights and Measures by the 51 national signatories of the "Meter Convention"—the treaty that governs the SI. Once equilibrated, these copies are used to calibrate all other mass standards of the member states in a long, unbroken sequence that propagates down to the weighing scales and other instruments employed in laboratories and factories around the globe.

It makes economic sense to have a stable, unchanging standard of mass, but evidence indicates that the mass of the IPK drifts with time. By observing relative changes of the other mass standards fabricated at the same time as the IPK and by analyzing old and new measurements of mass-related fundamental constants (which are thought not to change significantly over time), scientists have shown that the mass of the IPK could have grown or shrunk by 50 micrograms or more over the past 100 years. The drift could have been caused by such things as accumulated contamination from the air or loss from abrasion. Because the base units of the SI underpin worldwide science and industry (via the national standard calibration chains), ensuring that they do not vary with time is critical.

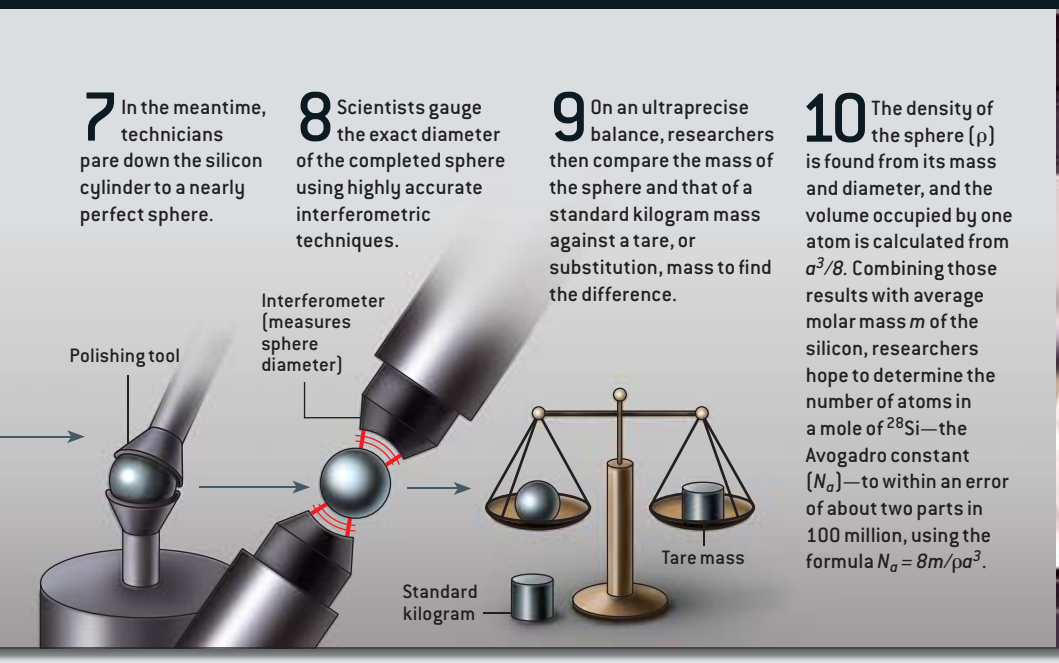
Based on Nature

THE SAME INCONSTANCY that plagues the definition of the kilogram previously affected the second and the meter. Scientists once defined the second in terms of the rate of rotation of the earth. In 1967, however, they redefined it to be "the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom." Metrologists introduced this change because the rotation rate of our planet is not constant, whereas the wavelength of the radiation

Overview/*Kilogram Redefined*

- For more than a century, metrologists have relied on a metal cylinder the size of a plum to standardize for the world the basic unit of mass, the kilogram. Continued technological progress requires that a new definition be developed, one based on a fundamental property of nature.
- Two methods are being pursued. One approach meticulously calculates the number of silicon atoms in a kilogram of pure silicon. The other effort employs an indirect comparison of mechanical and electrical power to measure the kilogram using length, time and quantum-mechanical effects.

RICK JONES (*scale on page 102*); COURTESY OF NATIONAL INSTITUTE OF METROLOGICAL RESEARCH, TORINO, ITALY (*preceding page*); JEN CHRISTIANSEN (*illustrations above and opposite page*)




SILICON SPHERE

emitted by cesium 133 during a specific transition—that is, the ticking of an atomic clock—does not alter with time and the measurement can be reproduced anywhere in the world.

Although the definition of the second is not based on an artifact, it suffers from its dependence on a particular transition of a specific atom, which unfortunately turns out to be more sensitive to electromagnetic fields than is desirable. The definition may need to be changed in the future to accommodate the even more precise optical clocks that physicists are now developing.

The definition of the meter, on the other hand, is firmer. The SI originally based the meter on an artifact—the distance between two lines inscribed on a highly stable platinum-iridium bar. In 1983 the meter definition was switched to "the length of the path traveled by light in vacuum during a time interval of $^1/_{299,792,458}$ of a second." This definition should also be resilient because it fixed the value of a key physical constant, the speed of light, at exactly 299,792,458 meters a second. Thus, progress in the control and measurement of the frequency of electromagnetic radiation (the number of sinusoidal vibrations a second) will merely improve the accuracy with which scientists can measure the meter—with no change in the unit's definition required.

Atomic Accounting

TO REDEFINE THE KILOGRAM in terms of a physical constant, metrologists measure the value of the constant as accurately as possible using the existing definition of the mass unit. This number can then be incorporated into the new definition to ensure a seamless transition between the old and new ones. Researchers can then employ the measurement method, in conjunction with the now fixed value of the constant, to determine mass according to the new definition.

One promising approach relates the kilogram to the mass of an atom by quantifying the kilogram as the mass of a certain number of atoms of a selected element. This route would fix the value of the Avogadro constant, which is defined as the number of atoms of a specific element in a mole—about 6.02×10^{23} atoms. (A mole is the amount of an element that has a mass in grams equal to the element's atomic weight; a mole of carbon 12 has a mass of 12 grams.) The problem with this strategy, however, is that it requires one to count enough atoms to make a weighable quantity of material for comparison with a kilogram mass. Because several physical effects limit the accuracy and resolution of balances to around 100 nanograms, a minimum of five grams of material would be needed to approach the target accuracy of approximately two parts in 100 million. Sadly, physicists cannot count out atoms rapidly enough; even if a counter capable of tallying individual atoms at a rate of one trillion a second could be produced, the device would take about seven millennia to tally enough carbon 12 atoms.

Scientists could, however, determine the number of atoms in a perfect crystal by dividing the volume of the crystal by the volume occupied by a single atom. If the crystal is then weighed and the mass of the atomic species that makes up the crystal is known relative to that of carbon 12, they can calculate the Avogadro constant from these data, thereby providing a path to the redefinition of the kilogram.

This more practical method, which is now being pursued, first measures the volume occupied by an atom by determining the regular spacing of atoms within a nearly perfect crystal (with a known number of atoms per unit cell) of known weight, close to one kilogram. Then, by determining the dimensions of the crystal, scientists can find the total volume, from which the mass of an atom in the sample can be calculated. The Avogadro constant, which is calculated from the ratio of the molar mass

CSIRO AUSTRALIAN CENTER FOR PRECISION OPTICS (*photograph*)

of an element to the mass of an atom, could then be derived from the results.

Although this plan is simple in concept, researchers have difficulty implementing it because of the extreme degree of precision it entails. Indeed, the high complexity and cost of this project mean that no one facility can hope to carry it out alone. Consequently, the load is being shared among a consortium of laboratories in Australia, Belgium, Germany, Italy, Japan, the U.K. and the U.S.—the International Avogadro Coordination. For this technique to work, the crystal must have an almost perfect structure; it must contain few voids or impurities. Project scientists chose to make the crystal out of silicon because the semiconductor industry has studied it closely and has developed procedures to grow large, practically perfect, single crystals. Once researchers had completed all the measurements of the crystal, they could relate the results to the carbon 12 definition of the mole using the extremely precise relative atomic masses of silicon and carbon obtained from mass spectrometers.

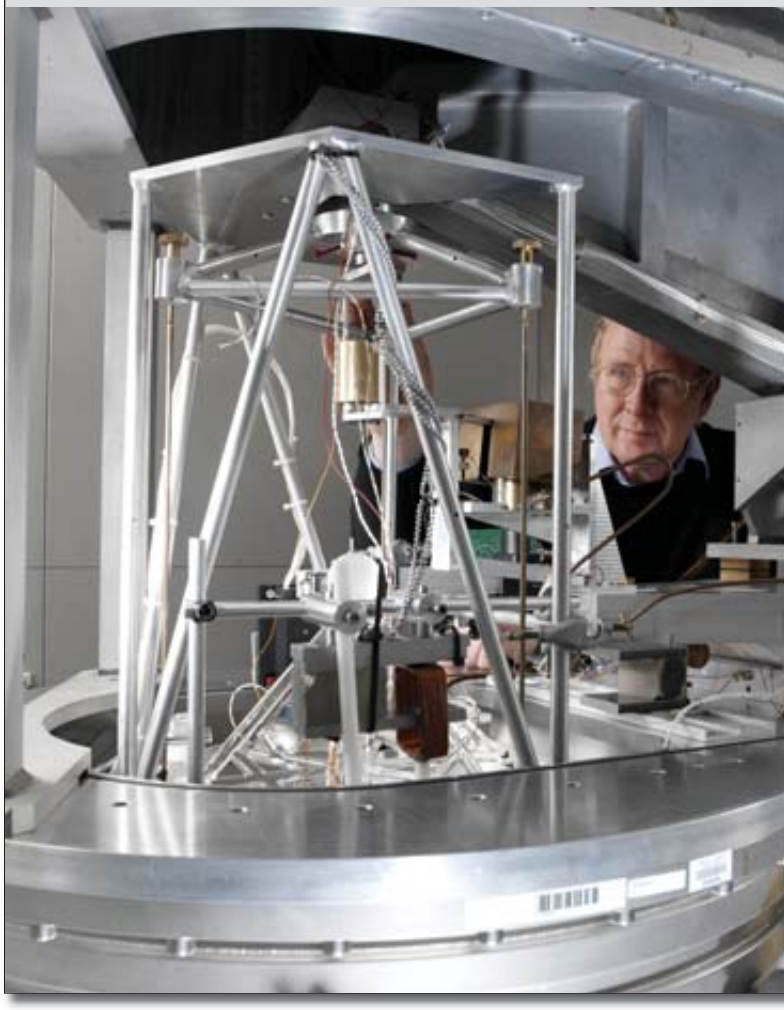
To begin the procedure, they cut several samples from a raw crystal. One was polished to form a one-kilogram sphere to measure [*see box on preceding two pages*]. Planners selected a rounded shape because a ball has no corners that could get knocked off and because craftsmen already knew how to hone silicon into a close approximation of a perfect sphere. Australian technicians fabricated a sphere with a diameter of 93.6 millimeters that departs from the ideal by no more than 50 nanometers. If each silicon atom were the size of a large marble (about 20 millimeters across), the sphere would equal the approximate size of the earth, and the distance between the highest and lowest "altitude" on its surface would be about seven meters (about 350 marbles in length).

To find the volume of the silicon sphere, researchers had to determine its average diameter to within the diameter of an atom. They first carefully reflected laser light of a known frequency off opposite sides of the sphere in a vacuum and gauged the difference in light paths (in wavelengths) with the sphere present and absent. This step enabled them to find its diameter in meters, as the wavelength of the light is equal to the (fixed) speed of light divided by the known laser frequency. Scientists then calculated the volume from the diameter, together with a few small corrections related to the slightly imperfect shape of the crystal and the optical properties of the surfaces.

Researchers obtained the volume occupied by one atom using combined x-ray and optical interferometry to find the distance between atomic planes in a sample cut from the raw crystal. Technicians machined several slots into the sample so that one part of the crystal could be moved reproducibly with respect to the rest of it while maintaining the angular alignment of the atomic planes. The sample was placed in a vacuum and illuminated with x-rays having a wavelength small enough to reflect easily from the atomic planes in the crystal. They then used the strength of this reflection, which varies according to the relative position of the atomic planes in the moving and stationary parts of the crystal, to count the number of plane spacings the repositioned part of the crystal had shifted. Scientists simultaneously measured the translation distance using a laser interferometer that used light of a known frequency. This technique determined the interplane spacing in meters. Using

FROM A WATT BALANCE TO A KILOGRAM STANDARD

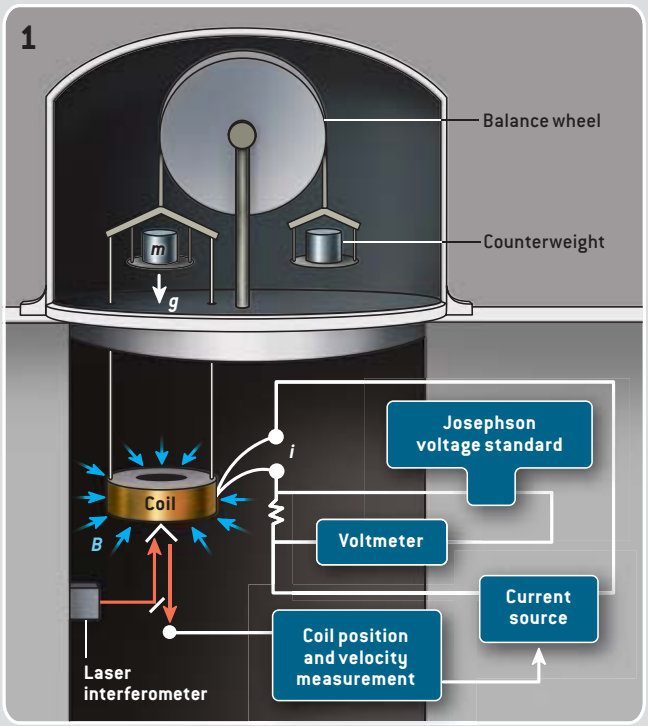
Another approach to redefining the kilogram quantifies a mass in terms of its energy equivalent. It relies on adjusting the force produced when a current passes through a wire in a magnetic field to balance exactly the weight of a mass. The procedure makes use of a sophisticated scale called a watt balance (*below*). On one side of the scale sits a simple counterweight (*diagrams*). On the other, a standard kilogram of mass *m* dangles above a horizontal coil of wire. The weight of the standard is the product of *m* times the acceleration caused by gravity *g*.

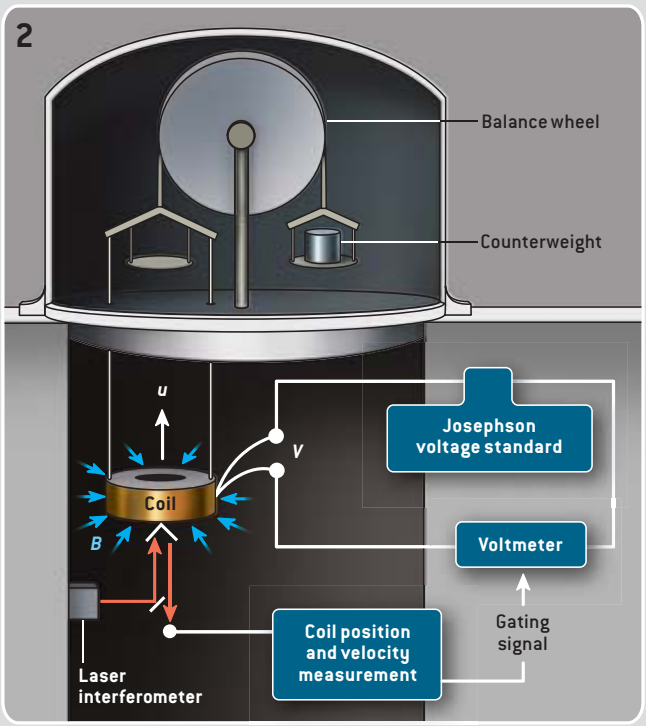


COURTESY OF NATIONAL PHYSICAL LABORATORY, U.K., © CROWN, 2005

THE AUTHOR

IAN ROBINSON, who received his M.A. from the University of Oxford and his Ph.D. from University College London, is an NPL Fellow at the U.K.'s National Physical Laboratory (NPL). He has worked on all three generations of the NPL watt balance (the latest design was completed recently) and chairs the Consultative Committee for Electricity and Magnetism working group on electrical methods to monitor the stability of the kilogram.





1 WEIGHING PHASE

In the first step, the coil dips into a radial magnetic field and an electric current passes through it. An induced electromagnetic force then acts on the coil, oriented opposite the force of gravity. If this electromagnetic force precisely balances the weight of the standard, one can calculate the standard's mass m as:

$$m = BLi/g$$

where B is the magnetic field strength, L is the length of wire in the coil, and i is the electric current. Unfortunately, in practice the product BL is almost impossible to gauge directly with sufficient accuracy.

2 MOVING PHASE

If, however, the coil moves at a constant velocity u at right angles to the magnetic field, the entire coil generates a voltage V that is equal to BLu. (This process is equivalent to the operation of an electric generator.) Voltage and velocity can both be measured very precisely. One can then eliminate the problematic product BL from the equation above:

$$m = Vi/gu$$

The final result equates mechanical and electrical power. The mechanical power measured is equivalent to that obtained if the mass is moved vertically with velocity u, whereas the electrical power is equivalent to that dissipated in an ideal resistor with voltage V across it and the current i passing through it. Because the two measurement phases are separated in time, however, the power is not real (scientists call it "virtual power"). These "virtual" measurements allow the technique to ignore the real power that is generated or dissipated in both phases of the experiment, which makes it possible to achieve the low uncertainties that are required.

During the experiment, several high-accuracy measuring systems monitor the watt balance. A laser interferometer measures the coil's movement, which is timed against an ultraprecise reference signal. A sensitive gravimeter (*not shown*) monitors the local pull of the earth's gravitational field. Other devices based on the Josephson effect and the quantum Hall effect [*see box on next page*] measure the voltage and current with extraordinary precision. Scientists can therefore link the mass of a kilogram to the Planck constant of quantum theory, the meter and the second with an extremely high degree of precision.

knowledge of the crystal structure, they then found the volume occupied by an atom.

Metrologists ascertained the mass of the crystal sphere by "substitution weighing" using a conventional balance and a "tare mass," whose mass must be stable but need not be known. They placed the sphere on a balance and compared it against a separate one-kilogram tare mass sitting on the other arm of the balance. They then substituted the sphere with a mass known in terms of the IPK mass standard and repeated the weighing process. Because the substitution was carried out so that the balance remained unaffected by the switch, the difference in the two readings gave the difference in mass between the sphere and the mass standard, which revealed the mass of the sphere. This method eliminated error arising from factors such as unequal lengths of the balance arms.

The researchers also analyzed other samples of the silicon material to establish the relative abundance of the various isotopes to account for their differing contributions to the molar mass of the sphere. To accomplish this task, they had to determine the proportion of the three isotopes—silicon 28, silicon 29 and silicon 30—present in the natural silicon crystal. For this step they used mass spectroscopy, which separates charged

JEN CHRISTIANSEN

isotopes according to their different charge-to-mass ratios.

The IAC has nearly completed work on the natural silicon spheres, having thus determined the number of atoms in a one-kilogram sphere with an accuracy close to three parts in 10 million. But this accuracy is not good enough. To achieve higher levels, the group is producing a sphere that consists almost entirely of a single isotope, silicon 28. Making such an object will cost between $1.25 million and $2.5 million. Gas centrifuges in Russia that were once employed to refine weapons-grade uranium are purifying the material for the new sphere. The consortium is aiming for an uncertainty in the final result of about two parts in 100 million before 2010.

Weighing Equivalent Energy

THE OTHER PATH to redefining the kilogram is based on the concept of measuring mass in terms of its equivalent energy, a principle that Albert Einstein explained using his famous equation $E = mc^2$, which relates mass and energy at the most fundamental level. Investigators would thus define mass in terms of the amount of energy into which it could (potentially) be converted. As is true of counting atoms, though, the techniques involved have considerable disadvantages. For example, large releases of atomic energy result when mass is converted into energy directly. Luckily, easier methods that compare conventional electrical and mechanical energy or power are feasible, provided that researchers can overcome problems associated with energy losses.

To get a sense of the obstacles to this type of approach, imagine using an electric motor to lift an object having mass m (against gravity). In an ideal situation, all the energy supplied to the motor would go into increasing the potential energy of the object. The mass could then be calculated from the electrical energy E supplied to the motor, the vertical distance d traveled by the object and the acceleration from gravity g, using the formula $m = E/gd$. (The acceleration caused by gravity would have to be gauged very accurately using a precision gravimeter.) In the real world, however, energy losses in the motor and other parts of the system would make an accurate measurement almost impossible. Although researchers have attempted similar experiments using superconducting levitated masses, accuracies better than one part in a million are hard to achieve.

About 30 years ago Bryan Kibble of the U.K.'s National Physical Laboratory (NPL) devised the method now known as the watt balance, which avoids energy-loss problems by measuring "virtual power" [*see box on preceding two pages*]. In other words, by designing a sufficiently clever, two-part procedure, scientists can sidestep the inevitable losses. The method links the standard kilogram, the meter and the second to highly accurate practical realizations of electrical resistance (in ohms) and electric potential (in volts) derived from two quantum-mechanical phenomena—the Josephson effect and the quantum Hall effect, both of which incorporate Planck's constant [*see box at right*]. In the process, the technique allows the value of the Planck constant to be measured very accurately.

In the watt balance, an object having mass m is weighed by suspending it from the arm of a conventional balance to which a coil of wire is also attached with a total length L hanging in a strong magnetic field B. A current i is passed through the coil to generate a force BLi, which is adjusted to exactly balance the weight mg of the mass (that is, $mg = BLi$). The mass and current are then removed, and in a second part of the experiment, the coil is moved through the field at a measured velocity u while the induced voltage V ($V = BLu$) is monitored. This second phase finds the value of the BL product, which is difficult to determine in any other way. If the magnet and coil are sufficiently stable, so that the BL product is the same in both parts

QUANTUM EFFECTS MEET CLASSICAL PHYSICS

Although the principles of the watt balance would be familiar to a 19th-century physicist, its ability to measure mass in terms of fundamental constants arises from two quantum effects discovered only within the past 45 years: the Josephson effect and the quantum Hall effect. Both phenomena occur at the temperature of liquid helium (4.2 kelvins) or below.

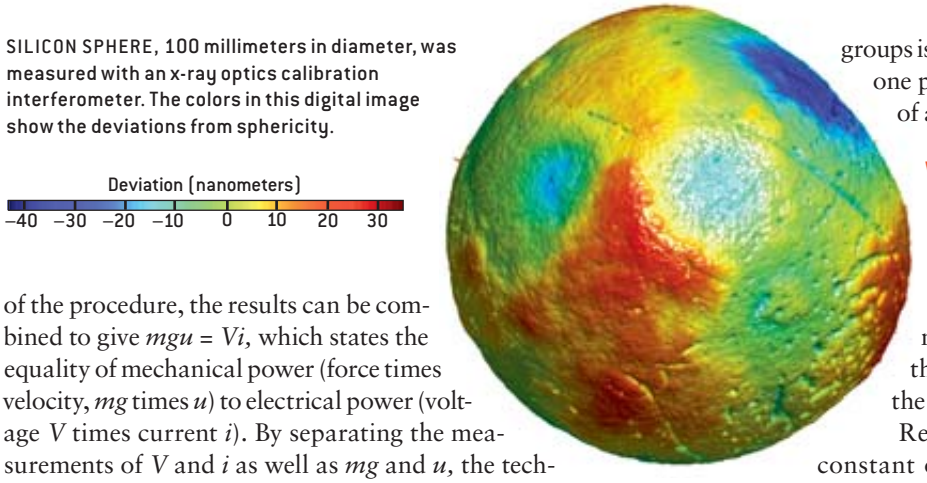
JOSEPHSON EFFECT

A Josephson junction consists of two superconductors separated by a small insulating gap that electron pairs can traverse in a process called quantum tunneling. If such a junction is illuminated with microwaves, the pairs of electrons in the superconductor absorb photons from the microwaves and jump the gap. Under these conditions, the voltage across the gap will be a small multiple of $hf/2e$, where h is Planck's constant, f is the frequency of the microwave radiation and e is the elementary charge. This relation is believed to be exact and provides a voltage standard of unparalleled accuracy.

QUANTUM HALL EFFECT

The standard Hall effect occurs in all conductors. The phenomenon occurs when an electric current is passed through a material that is in a magnetic field. The magnetic field generates a force on the charge carriers in a direction perpendicular to both the field and the current. These conditions cause electric charge to build up on the sides of the device, producing both a voltage and a corresponding electric field that opposes the magnetic force on the carriers. This voltage is proportional both to the applied current and the magnetic field, so the effect can be thought of as a resistance to electric flow (the Hall resistance), which is proportional to the magnetic field.

In specially fabricated semiconductors that are subjected to low temperatures (in the range of 1.2 to 0.03 kelvin) and high magnetic fields, the quantum-mechanical version of the Hall effect can be observed. Under these conditions, and over small ranges of magnetic field, the quantum Hall resistance becomes independent of both the magnetic field and the semiconductor material; it is equal to h/ne^2, where n is a small integer. This equation provides scientists with a quantum-based standard for measuring electrical resistance.



SILICON SPHERE, 100 millimeters in diameter, was measured with an x-ray optics calibration interferometer. The colors in this digital image show the deviations from sphericity.

of the procedure, the results can be combined to give $mgu = Vi$, which states the equality of mechanical power (force times velocity, mg times u) to electrical power (voltage V times current i). By separating the measurements of V and i as well as mg and u, the technique yields a result that is not sensitive to the loss of real power in either part of the experiment (that is, heat dissipated in the coil during weighing or frictional losses during moving), so the apparatus can be said to have measured "virtual" power.

Scientists determine the electric current in the weighing phase of the watt balance procedure by passing it through a resistor. This resistance is specially gauged using the quantum Hall effect, which permits it to be described in quantum-mechanical terms. The voltage across the resistor and the coil voltage are measured in terms of quantum mechanics using the Josephson effect. This last result allows researchers to express the electrical power in terms of Planck's constant and frequency. Because the other terms in the equation depend only on time and length, researchers can then quantify the mass m in terms of Planck's constant plus the meter and the second, both of which are based on constants of nature.

The method's principle is relatively straightforward, but to achieve the desired accuracy of approximately one part in 100 million, scientists must determine the major contributing quantities with an accuracy at the limit of many of the best available techniques. Besides measuring g very accurately, they have to perform all the procedures in a vacuum to eliminate the effects of both air buoyancy during the weighing process and the air's refractive index during the velocity measurement (which uses a laser interferometer). Researchers must also precisely align the force from the coil to the vertical direction and perform angular and linear alignments of the apparatus to a precision of at least 50 microradians and 10 microns, respectively. Finally, the magnetic field has to be predictable between the two modes of the watt balance, a condition requiring that the temperature of the permanent magnet vary slowly and smoothly.

Three laboratories have developed watt balances: the Swiss Federal Office of Metrology, the National Institute of Standards and Technology (NIST) in the U.S., and the NPL. Meanwhile the staff of the French National Bureau of Metrology is assembling prototype equipment, and that of the International Bureau of Weights and Measures is designing an apparatus. Ultimately these efforts will yield five independent instruments with varying designs, so the extent to which their results agree will indicate how well researchers have identified and eliminated systematic errors in each case. The long-term goal of these groups is to measure Planck's constant to around one part in 100 million, with the possibility of approaching five parts in a billion.

Weighty Future

THE LATEST RESULTS from the work on the Avogadro constant and those from the NPL and NIST watt balances differ by more than one part in a million. Researchers must reconcile this discrepancy before a redefinition of the kilogram will be possible.

Redefinition in terms of the Avogadro constant or Planck's constant will have widespread effects, reducing reported uncertainties associated with those constants. Moreover, if Planck's constant and the elementary electric charge are fixed (by combining, for example, watt balance and calculable capacitor measurements), many other important constants would also be fixed.

The International Committee for Weights and Measures has recommended that national measurement laboratories continue their efforts aimed at measuring the fundamental constants that support the redefinition process. Researchers hope that these steps will lead to new standards not only for the kilogram but the ampere, the kelvin and the mole by 2011.

Once the redefinition is complete, a few nations will build or maintain the equipment necessary for implementing the definition directly. Those that do not will have their standards calibrated using a consensus value for the kilogram derived from the laboratory work. Still, fears of damaging or contaminating a single master reference standard should fall away because comparisons between national standards and a working standard based on the new definition could be performed as needed. The new definition would allow authorities to adjust the world mass scale in tiny steps every so often to keep it free of drift and fully locked to the best—the latest consensus and independently confirmed—value of the SI unit of mass. Such a system would be robust and stable, allowing scientific and technological progress to continue unabated. SA

MORE TO EXPLORE

Gravimetry. Wolfgang Torge. Walter de Gruyter, 1989.

Comprehensive Mass Metrology. Edited by M. Kochsiek and M. Gläser. Wiley-VCH, 2000.

History and Progress in the Accurate Determination of the Avogadro Constant. P. Becker in *Reports on Progress in Physics,* Vol. 64, No. 12, pages 1945–2008; December 2001.

Josephson Voltage Standards. J. Kohlmann, R. Behr and T. Funck in *Measurement Science and Technology,* Vol. 14, No. 8, pages 1216–1228; August 2003.

The Quantum Hall Effect as an Electrical Resistance Standard. B. Jeckelmann and B. Jeanneret in *Measurement Science and Technology,* Vol. 14, No. 8, pages 1229–1236; August 2003.

Replacing the Kilogram. B. P. Kibble and I. A. Robinson in *Measurement Science and Technology,* Vol. 14, No. 8, pages 1243–1248; August 2003.

Tracing Planck's Constant to the Kilogram by Electromechanical Methods. A. Eichenberger et al. in *Metrologia,* Vol. 40, No. 6, pages 356–365; December 2003.

SET THEORY

By Patrick Merrell

Think of this crossword as a Venn diagram consisting of two sets—one right side up, the other rotated 180 degrees. The shaded section in the middle represents the overlap of the two sets, with answers in this area working for both sets. How is this possible? All will become clear as you solve the puzzle. The puzzle also contains 12 clues related to articles that appeared in *Scientific American* in 2006—one for each month. Visuals from the referenced articles frame the grid. Find the answers at www.sciam.com/ontheweb and in next month's issue.

ACROSS

1 101 course material
7 Bonobos and gibbons
11 Intertwine
15 Biped whose color vision far surpasses that of humans (***July***)
19 Misbehaves
20 Lab partner
22 Unique individual
23 **Comment about the puzzle you're doing that's 100 percent true, literally speaking**
25 Start of a recipe step
26 Swiss winner of the 1991 Nobel Prize in Chemistry
27 Nonelectrical plugs?
28 Narrow inlets
29 Rigid
30 ER assistants
31 Vessels found in some pharaohs' tombs
33 Negatively charged elementary particle
35 Wall St. debut
37 "Scram!"
38 Matrix
39 Reflective-sounding cells that could help explain autism (***November***)
42 Rio beach
45 Early automaker
46 Jordanian site of ancient rock-cut monuments
47 Watt prefix
48 Leonhard Euler's 18th-century Latin squares are an early relative of this modern creation (***June***)
50 Meditative sounds
51 Grand or hand follower
55 Earthquake
57 Unspecified amount
58 Quaker cereal featuring torus-shaped pieces
59 Mad scientist's helper
60 "In what way exactly?"
63 Stalemated sequence in a simple strategy game
64 "My apologies"
67 FDA overseer
68 Moves like a paramecium
70 New XY human

DOWN

1 Big name in pills
2 Nut with a woody cupule
3 Tests one's nerves?
4 Pac. stopovers
5 Factor that explains sophisticated tool use by some orangutans (***April***)
6 Epidermis-protecting letters
7 Flameless burners in the lab
8 Explodes
9 Latitude 90° N worker?
10 ____-mo
11 Guatemalan, for one
12 Turkish title
13 Culinary styles
14 Some M.I.T. grads
15 Wake maker
16 One seventh of a rainbow
17 Colorfully named minnow
18 Preedited versions
21 They prove one is human
24 Actor Martin of *Ed Wood*
29 Becomes acrid
32 Crater projections
33 Word with Way
34 Hindic language
36 Type of dog that could prove useful in finding cancer cures (***December***)
38 Grind
39 One of perhaps hundreds in the solar system (***August***)
40 Turbine measures, briefly
41 π, for one
42 "____ miracle!"
43 Ball-shaped hammer part
44 Like the Mojave
49 1957 physics Nobelist Tsung-____ Lee
50 Surprised reactions
52 Sci. of farming
53 Hide/hair connector
54 Dull, as a lecture
56 Hardness scale name
58 ____-pah band
61 Sci-fi doctor
62 Dir. equal to 202.5°
63 Nu followers
64 Mag. output
65 Sun.'s neighbor
66 Crystals that make blankets
68 Ramón y Cajal's "You bet!"
69 Really impress

ACROSS

71 Filament
77 Click made with two digits
81 Highway division
85 Where the wild things are, perhaps
89 Affixable with heat
90 Conic sections
92 A.D. part
93 **Considers both sides of a problem, literally with this puzzle**
95 In many locations, it's the cheapest new source of electricity (***September***)
96 Give to a church
97 www.sciam.com, e.g.
98 Abbreviated titles for Curie and Bovary
99 *Mendelian inheritance* (genetic reference catalogue)
100 Defeating sound
101 Winemaking prefix
103 *Quercus* ____ (white oak) or Jessica of *Dark Angel*
105 Every breath you take
107 Ingested
108 Regretted
109 Dip reflecting an increasingly negative reaction as androids become eerily human (***May***)
112 Chuck Yeager or Wiley Post
115 Orderly
116 Simple kind of question
117 Charge for George and Joy Adamson
118 Extensive structures built by Central American Indians 2,500 years ago (***October***)
120 Flesh or blood finale
121 Fellow with lots of potential energy
125 Per ____ (yearly)
127 Sounds heard at spas
128 White Sands winter hrs.
129 Unit that can be patented—nearly 20 percent of human ones have been (***February***)
130 Stimulus counterpart
133 "Or ____ thought"
134 Ambled, Western-style
137 Atomic wts., e.g.
138 Moves like a paramecium
140 "Quiet"

DOWN

71 Mouth residues
72 A crowd, to Pierre Dusart
73 Underground network
74 Egyptian symbol of life
75 Beat by a proboscis
76 Material that new techniques might soon affordably read, allowing for truly personalized medicine (***January***)
77 Richard's running mate
78 NIH part: Abbr.
79 Nonscientific course of study
80 Canine's hirsute extremity
81 Unenviable pole position
82 Wings: Latin
83 Discouraging sort
84 NASA's third
85 Green suburban quadrangle
86 Zoological specimen
87 Possessed with at birth
88 Comedian Dangerfield
91 India's Mumbai, previously
94 Cold, treeless area
99 Modern-day Persian
102 Fair-hiring org.
103 Plants yielding a blue dye
104 Digital readouts, for short
106 They're stuck in hosps.
108 Accumulated, as debts
109 Home of Bonneville Salt Flats
110 Andrei Sakharov's denial
111 Beaver hangout
112 Controversial apple spray
113 Creepy one that clings
114 Cosmic rays, a danger during long spaceflights, are actually these charged particles (***March***)
119 110-Down, to James Watt
120 Egyptian fertility goddess
122 Rocketry expert Willy
123 Hydrocarbon suffix
124 Like Martian soil
126 Lunar peak
128 Arm tattoo cliché
131 "This minute!"
132 Fed. support benefit
133 It's 110 in binary code
134 Mag. submissions
135 Resistance unit
136 Display
138 N.Y.C. district with galleries
139 Court

April
5-Down

June
48-Across

July
15-Across

August
39-Across

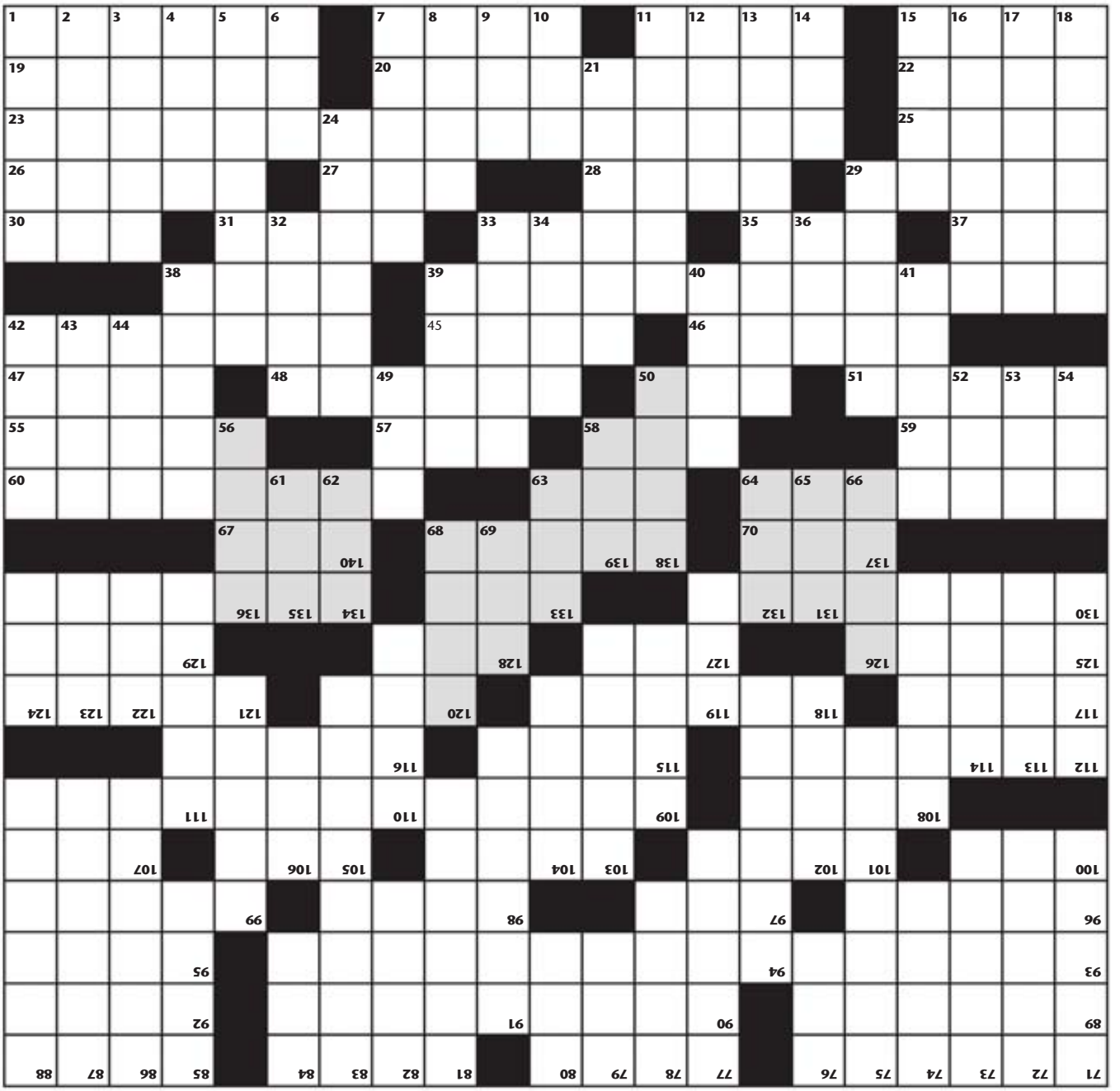
November
39-Across

December
36-Down

THE AUTHOR

PATRICK MERRELL is a professional puzzlemaker and graphic designer. He creates word, visual and logic puzzles of every kind for both adults and children. His crossword puzzles ...

Continued below



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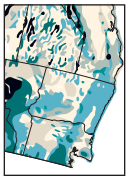
... appear regularly in the *New York Times* as well as many other newspapers, magazines and books. He has written 20 books and illustrated 100 others (www.patrick.merrell.org).

THE AUTHOR

October
118-Across



September
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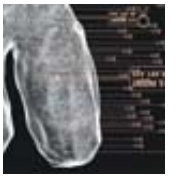

February
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January
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TITLE ART BY PATRICK MERRELL; PERRY VAN DUIJNHOVEN, FROM *AMONG ORANGUTANS: RED APES AND THE RISE OF HUMAN CULTURE*, BY CAREL VAN SCHAIK. THE BELKNAP PRESS OF HARVARD UNIVERSITY PRESS, © 2004 BY THE PRESIDENT AND FELLOWS OF HARVARD COLLEGE (*April*); EMANUEL HANDMANN, 1753, ORIGINAL PASTEL AT KUNSTMUSEUM BASEL (*June*); MARTIN HARVEY *Peter Arnold, Inc.* (*July*); NASA/JPL/SSI (*Aug.*); JEAN-FRANCOIS PODEVIN (*Nov.*); DK LTD. *Corbis* (*Dec.*); STUART BRADFORD (*Jan.*); BRYAN CHRISTIE DESIGN (*Feb.*); PAT RAWLINGS *SAIC* (*March*); OSAKA UNIVERSITY INTELLIGENT ROBOTICS LABORATORY (*May*); JEN CHRISTIANSEN (*Sept.*); © ROB WOOD *Wood Ronsaville Harlin, Inc.* (*Oct.*)

LITHIUM BATTERIES

Hot Commodity

Several large recalls of lithium-ion batteries used in notebook computers have raised questions about how these power packs could overheat enough to erupt in flames. Equally valid is the question of why accidents don't happen more often, given that very few occur among hundreds of millions of batteries sold annually.

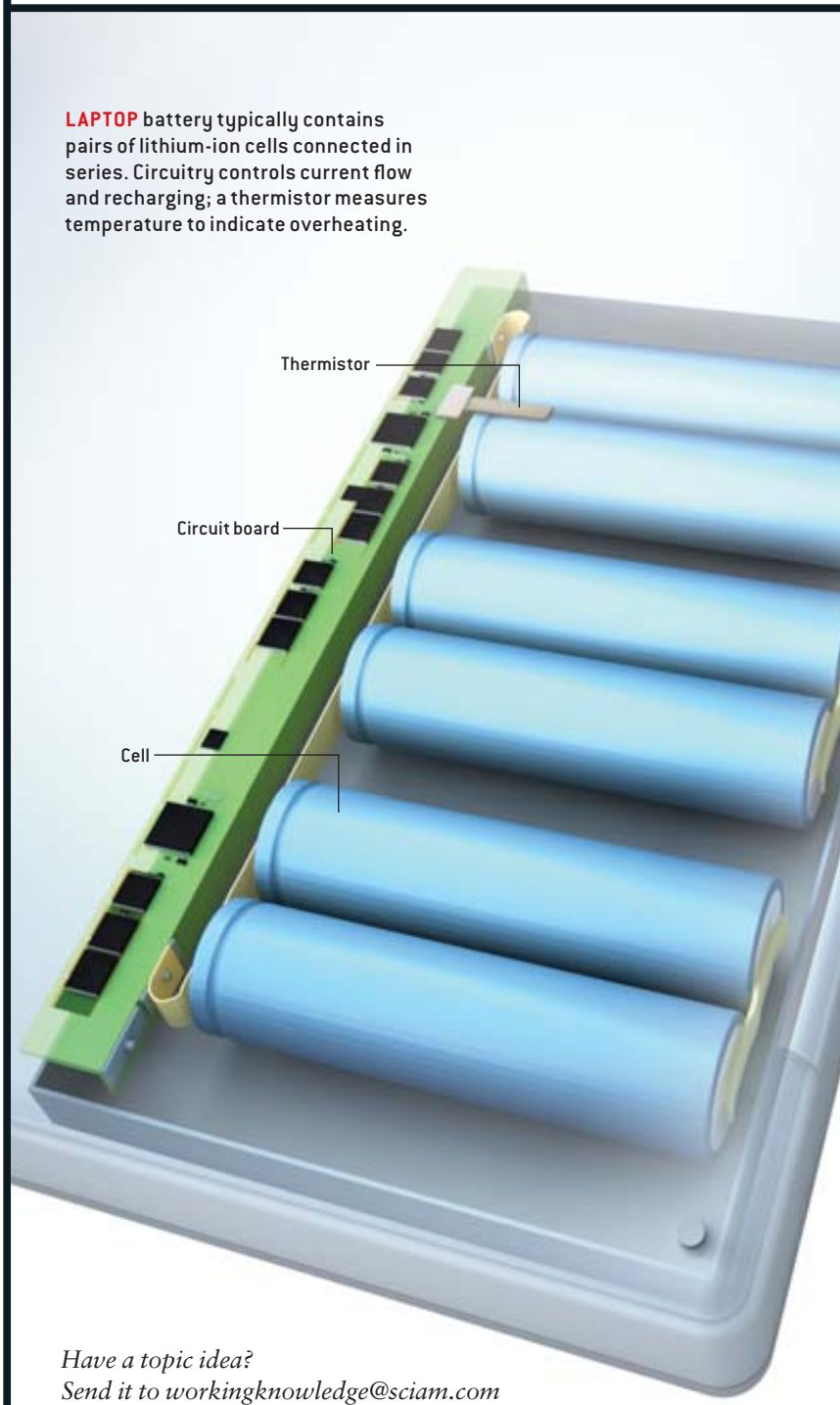
Lithium-ion cells exploit various chemistries, but virtually all rechargeable varieties, including those in cameras and in cell phones, use lithium cobalt oxide in the cathode and graphite in the anode [*see illustrations*]. Although this formulation is "inherently somewhat unsafe," according to Gerbrand Ceder, professor of materials science at the Massachusetts Institute of Technology, careful manufacturing and built-in safety devices have limited accidents to a handful. Still, Ceder explains, "battery makers have been pushing the state of charge" in a given cell because of electronics makers' demands for longer running time, so "there is now less margin for error." By stuffing more ions into the package, manufacturers have quadrupled energy capacity since commercial introduction in 1991.

Indeed, what was once a boutique product is now a commodity. The drive to raise capacity yet lower cost "encouraged manufacturers to take more risks," says Christina Lampe-Onnerud, co-founder of Boston-Power in Westborough, Mass., begun in 2005 to produce new lithium-ion battery types. "The safety mechanisms of five years ago were adequate for the level of energy in those cells," she adds, "but the push for capacity will outpace those mechanisms."

New safety devices and formulations that produce more current with less heat are being prototyped. Brisk work in the burgeoning electric and hybrid vehicle industry in particular "will create much safer cathode materials that will penetrate the consumer electronics industry," Ceder says. New metal oxides may appear in cathodes, and anodes may move from a carbon base to a silicon base. Yet until these materials prove out in testing, Lampe-Onnerud points out, more creative system design is the key to safe operation. "The industry has been pushing a single chemistry harder and harder for a wide range of applications," she says. "It's time to tailor-make different battery systems for different applications."

—Mark Fischetti

LAPTOP battery typically contains pairs of lithium-ion cells connected in series. Circuitry controls current flow and recharging; a thermistor measures temperature to indicate overheating.



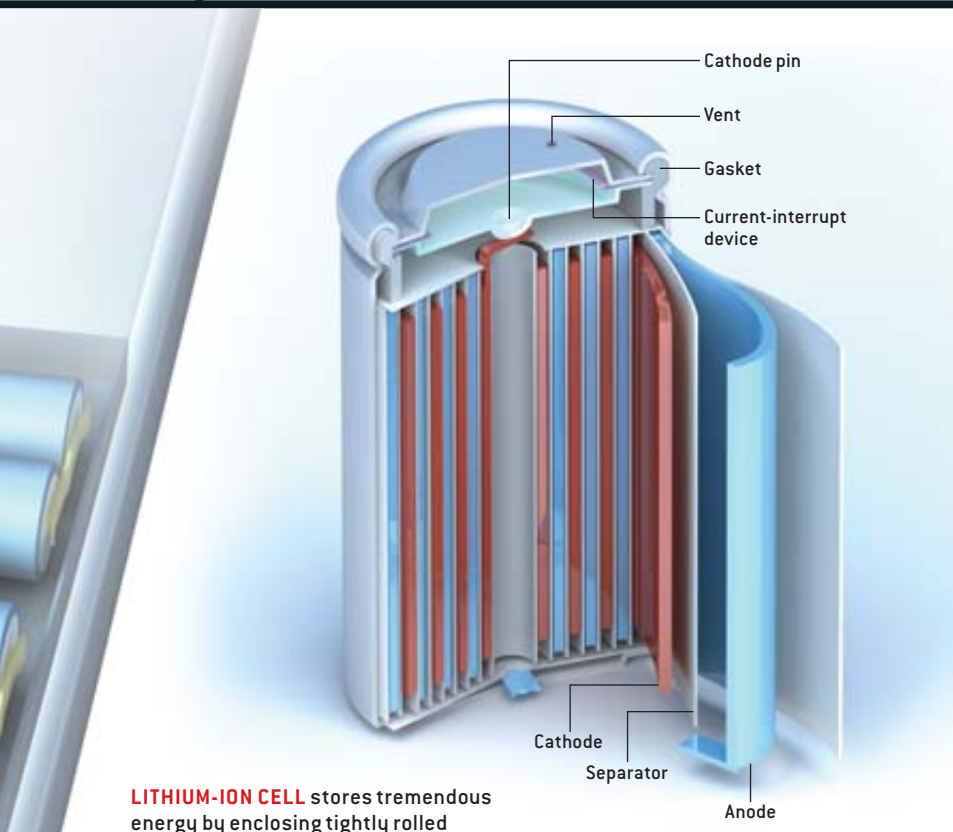
Have a topic idea?
Send it to workingknowledge@sciam.com

DID YOU KNOW...

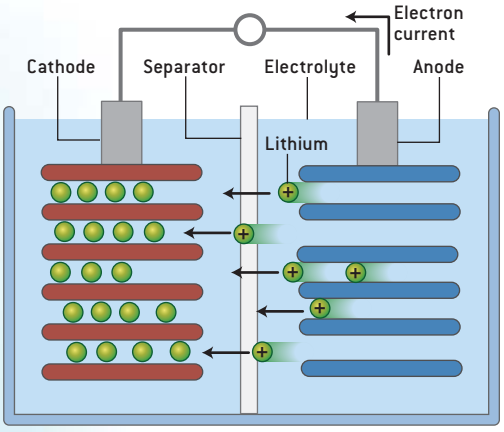
PROTECT YOURSELF: Lithium burns violently when exposed to even traces of moisture—as little as the humidity in air—so never try to pry open a battery. Do not douse a battery fire with water, which will incite flames; use a chemical-based extinguisher. A cell's housing can become dangerously hot or catch fire if the cell greatly overheats (which is more likely if it is fully charged); therefore, do not leave products on hot surfaces (windowsill heater) or in the sun, especially inside a car. Also, avoid shunting the battery's leads.

TESLA'S RIDE: Silicon Valley entrepreneur Martin Eberhard started Tesla Motors two years ago and this past summer unveiled the Tesla Roadster. The souped-up prototype is the first all-electric vehicle to use lithium-ion batteries: 6,831 of them. The car leaps from zero to 60 miles per hour in four seconds; its range between charges is reportedly 250 miles. The company says controllers that monitor each cell can shut down the entire pack in an instant, even if a cell catches fire. Other makers are experimenting with lithium nickel manganese oxide.

LIFE SPAN: All batteries degrade, but lithium-ion cells erode faster when highly charged and warm; an average notebook battery kept at full charge at 25 degrees Celsius will irreversibly lose about 20 percent of its capacity a year, according to studies. Keeping a cell at half-charge in the refrigerator could extend its life.

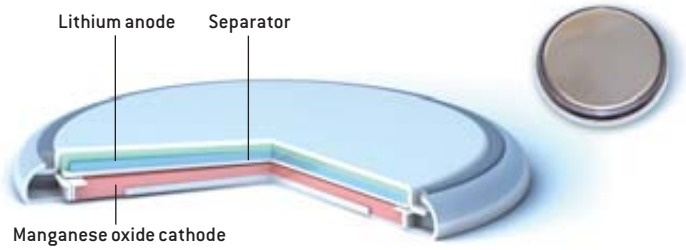


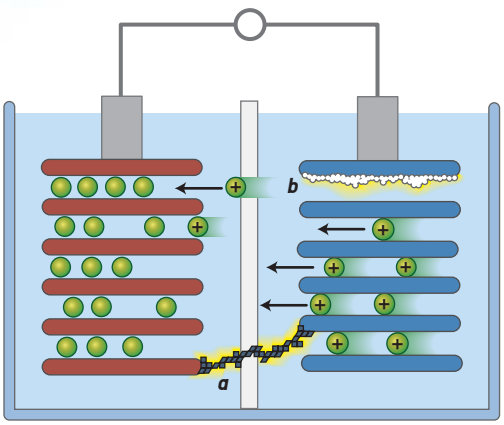
LITHIUM-ION CELL stores tremendous energy by enclosing tightly rolled sheets of cathode and anode, isolated by a separator, all soaked in an electrolyte. To prevent overheating, a vent allows gas from an errant chemical reaction to escape; the gasket blows if gas builds too fast, disabling the cell. If the cell is shorted externally, the rapid discharge triggers the current-interrupt device, which disconnects the cell.



CHEMICAL REACTION creates battery power. Lithium held in the anode ionizes in the electrolyte (a lithium salt) and migrates through the porous plastic separator to the cathode. The reaction frees electrons, which flow as external current. Applying an external voltage to the cathode drives ions back to the anode, recharging the cell.

BUTTON CELL creates current by moving lithium ions across an electrolyte separator. The flow cannot be reversed; the cell cannot be recharged.





OVERHEATING can result if metallic particles from defective manufacturing (the prime suspect in recent battery recalls) link the cathode and anode through the separator (*a*); this connection will shunt current, creating excessive heat. That heat can degrade materials enough to initiate a runaway reaction that becomes so hot that components begin to burn. A short can also occur if lithium metal from undesired chemical reactions accumulates (*b*).

BRYAN CHRISTIE DESIGN (*cutaways*); JEN CHRISTIANSEN (*schematics*); EMILY HARRISON (*photograph*)

Darwin at the Zoo

DID HUMANS INVENT RIGHT AND WRONG, OR ARE THESE FEELINGS PART OF THE INHERITANCE FROM OUR PRIMATE ANCESTORS? **BY JONATHAN WEINER**

PRIMATES AND PHILOSOPHERS: HOW MORALITY EVOLVED
by Frans de Waal. Edited by Stephen Macedo and Josiah Ober
Princeton University Press, 2006 ($22.95)

It was not until a year and a half after his voyage on board the *Beagle* that Charles Darwin first came face to face with an ape. He was standing by the giraffe house at the London Zoo on a warm day in late March of 1838. The zoo had just acquired an orangutan named Jenny. One of the keepers was teasing her—showing her an apple, refusing to hand it over. Poor Jenny "threw herself on her back, kicked & cried, precisely like a naughty child," Darwin wrote in a letter to his sister.

In the secret notebooks that he kept after the voyage, Darwin was speculating about evolution from every angle, including the emotional, and he was fascinated by Jenny's tantrum. What is it like to be an ape? Does an orangutan's frustration feel a lot like ours? Might she cherish some sense of right and wrong? Will an ape despair because her keeper is breaking the rules—because he is just not playing *fair?*

Our own species has been talking, volubly and passionately, for at least 50,000 years, and it's a fair guess that arguments about right and wrong were prominent in our conversation pretty much from the beginning. We started writing things down 5,000 years ago, and some of our first texts were codes of ethics. Our innumerable volumes of scripture and law, our Departments of Justice, High Courts, Low Courts, and Courts of Common Pleas are unique in the living world. But did we human beings invent our feeling for justice, or is it part of the package of primal emotions that we inherited from our ancestors? In other words: Did morality evolve?

Dutch-born psychologist, ethologist and primatologist Frans de Waal has spent his career watching the behavior of apes and monkeys, mostly captive troupes in zoos. As a young student, he sat on a wooden stool day after day for six years, observing a colony of chimpanzees at the Arnhem Zoo. Today he watches chimpanzees from an observation post at Emory University's Yerkes National Primate Research Center in Atlanta and at other zoos and primate centers. His work, along with primatologist Jane Goodall's, has helped lift Darwin's conjectures about the evolution of morality to a new level. He has documented tens of thousands of instances of chimpanzee behavior that among ourselves we would call Machiavellian and about as many moments that we would call altruistic, even noble. In his scientific papers and popular books (including *Chimpanzee Politics, Our Inner Ape* and *Good Natured*), he argues that Darwin was correct from that first glimpse of Jenny at the zoo. Sympathy, empathy, right and wrong are feelings that we share with other animals; even the best part of human nature, the part that cares about ethics and justice, is also part of nature.

EMPATHY: A juvenile chimpanzee consoles a screaming adult male who was defeated in a fight.

FRANS DE WAAL

De Waal's latest book, *Primates and Philosophers,* is based on the Tanner Lectures that he delivered at Princeton University's Center for Human Values in 2004. In this book he tries—as he has many times before—to refute a popular caricature of Darwinism. Many people assume that to be good, be nice, behave, play well with others, we have to rise above our animal nature. It's a dog-eat-dog world out there—or, as the Romans put it, *homo homini lupus,* man is wolf to man (a curious proverb for a people whose found-

ing myth was the suckling by a wolf of the infant twins Romulus and Remus).

Thomas Henry Huxley, Darwin's self-appointed bulldog, promoted this dark, cold view of life in a famous lecture, *Evolution and Ethics*. "The ethical progress of society depends, not on imitating the cosmic process, still less in running away from it, but in combating it," he declared. In Fyodor Dostoyevsky's *The Brothers Karamazov,* Ivan puts it another way: if there is no God, then we are lost in a moral chaos. "Everything is permitted." De Waal calls this "Veneer Theory." In this view, human morality is a thin crust on a churning urn of boiling funk.

In reality, de Waal reminds us, dogs are social, wolves are social, chimps and macaques are social, and we ourselves are "social to the core." Goodness, generosity and genuine kindness come just as naturally to us as meaner feelings. We didn't have to invent compassion. When our ancestors began writing down the first codes of conduct, precepts, laws and commandments, they were elaborating on feelings that evolved thousands or even millions of years before they were born. "Instead of empathy being an endpoint," de Waal writes, "it may have been the starting point."

Back in the 1950s and 1960s, when animal psychologists talked about "sympathy" and "empathy," they always put those words between quotation marks, de Waal notes. Now he wants to take away the quotation marks. He describes one of his best-known demonstrations that animals care about fairness. In the experiment, he had pairs of capuchin monkeys perform simple tasks in their cages. For successfully completing each task they would get a reward, sometimes a slice of cucumber, sometimes a grape. All the monkeys would work for and eat the cucumber slices, but they preferred grapes. If one monkey kept getting paid in cucumber and it could see that its partner in the next cage was getting grapes, it would get mad, like Darwin's Jenny. After a while the monkey would refuse to eat or throw the cucumber right out of the cage.

Is de Waal right about all this? In the second half of *Primates and Philosophers,* his arguments are critiqued by a series of commentators, all of whom have written important studies of evolutionary ethics. They cite Freud, Kant, Hume, Nietzsche and Adam Smith. They circle and circle around those pairs of capuchin monkeys:

"A capuchin rejects a cucumber when her partner is offered a grape—is she protesting the unfairness, or is she just holding out for a grape?" writes Christine M. Korsgaard, Arthur Kingsley Porter Professor of Philosophy at Harvard University.

"Of course, if the lucky capuchin were to throw down the grape until his comrade had a similar reward, that would be *very* interesting!" writes Philip Kitcher, John Dewey Professor of Philosophy at Columbia University.

They disagree, they discuss, they bicker a little, like all primates and philosophers. They illuminate not only ageless questions of ethics but also current concerns such as the Geneva convention and "why universal empathy is such a fragile proposal," as de Waal writes in his response to his critics. By the end of the book it seems clear that we can no longer look at morality as a sort of civilized veneer on a cold and selfish animal, even though that view goes back long before Darwin went to the zoo. Its origin lies in the Western concept of original sin—when Adam and Eve ate their first apple. SA

Jonathan Weiner won a Pulitzer Prize in 1995 for The Beak of the Finch. *He teaches science writing in Columbia University's Graduate School of Journalism.*

Continued on page 119

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THE EDITORS **RECOMMEND**

ALL THINGS RECONSIDERED: MY BIRDING ADVENTURES
by Roger Tory Peterson. Edited by Bill Thompson III. Houghton Mifflin, 2006 ($30)

BIRD SONGS: 250 NORTH AMERICAN BIRDS IN SONG
by Les Beletsky. Chronicle Books, 2006 ($45)

"All Things Reconsidered" was the title of Peterson's monthly column in *Bird Watcher's Digest*, which he wrote from 1984 until his death in 1996. Thompson, editor of the *Digest*, has chosen 40-odd columns and illustrated them with Peterson's own photographs (the great naturalist was nearly as passionate about photography as he was about painting). These are the best of Peterson's chatty columns, in which he shared his birding adventures—from the hot plains of the Serengeti, where he stabilized his long lens on "a cloth bag filled with rice," to freezing water off the coast of Maine, where his boat capsized as he, then in his 80s, was filming a documentary.

One wonders what Peterson would have made of *Bird Songs*, an audio book that plays, with remarkable clarity, the songs of the 250 birds it profiles. The audio component, built right into the book, has a speaker and an LCD display and is extremely easy to operate. The bird songs, from the collection of the Cornell Laboratory of Ornithology, are complemented by Beletsky's relevant and compact text (he is a wildlife biologist and writer) and beautifully straightforward color illustrations by four different artists. But you buy this book for the sound. Most likely, Peterson would have loved it.

News from Down Under

A REVIEW OF RECENT STORIES ABOUT THE MIND AND SOME OF THE BODY **BY STEVE MIRSKY**

It came as quite a shock recently when the stupidest thing I've ever heard turned out to come from England. I had assumed it would be from the U.S., but no. Anyway, here it is. A government minister said that some pregnant British teenagers were purposely smoking during their entire pregnancies to try to have low-birth-weight babies, which would make for easier deliveries.

Even more breathtaking than smoking itself, isn't it? Take a moment to get a bandage for where you hit your head when you passed out just now. I reiterate—this is the stupidest thing I've ever heard (and that really is saying something, especially after we within the reality-based community have watched the past five years play out).

A magazine for nurses reported that the British minister of public health, Caroline Flint, revealed that young women and health professionals had told her about this smoke-during-pregnancy concept. She discussed the strategy at a conference of the British Labor Party. Ironically.

For any women just being exposed to the tar-and-nicotine-delivery-delivery-system idea and thinking it may be just what the doctor ordered, find a new doctor. Low birth weight puts a baby at risk in numerous unhappy ways and does little or nothing to mitigate the pain of delivery. Besides, there are various effective pain-control options, including drugs. As a man, I'll never be blessed with the searing agony of passing an entire human being through an orifice, but were I faced with that prospect and offered pain medication, I would absolutely quote Molly Bloom: "yes I said yes I will Yes." (Which is, coincidentally, precisely how Molly wound up eventually wondering about pain-free childbirth, but that's another long story with nary a hint of punctuation.)

In other news below the waist, when I recently heard a New York plastic surgeon hawking butt jobs on the radio—there, that got your attention—I searched the Web for more information about this new method of attaining a foxy derriere. Strictly out of professional curiosity, rest assured.

A procedure familiar to aficionados of the movie *Saving Silverman,* the buttock implant is apparently making great inroads in the U.S. According to the American Society for Aesthetic Plastic Surgery, some 4,500 such procedures were done in 2004 and 2005, with another 10,000 simple buttock lifts having been performed in those two years. The surgeries typically cost somewhere between $4,000 and $5,000. They are, however, 100 percent successful. Because if people find out you had one, they will definitely point at you and say, "Look at that ass." (I realize that I'll be accused of getting on my high horse about this. But, see, I haven't had this kind of surgery, so I can still get on a horse.)

Finally, this story from McGill University, north of the border. Researchers there used infrared imaging of thermal activity for the first time in an attempt to measure sexual arousal rates. Study subjects were shown sexually explicit films while researchers recorded the thermal activity of subjects' genital areas. (Subjects and scientists were both thus able to say, "Watch where you're pointing that thing.") Men and women required virtually the same amount of time to become aroused, contrary to conventional wisdom. But it was the control part of the experiment that really jumped out at me: subjects were shown a video montage that included *The Best of Mr. Bean* and Canadian tourism travelogues. If you find such material arousing and you are not a Royal Canadian Mounted Police officer married to Rowan Atkinson, you should seek immediate counseling. Once you get off your horse.

Editors' note: In a discussion of New York City landmarks worth protecting [August], we listed Nobel laureates living or working in the five boroughs. We neglected to include 1998 physiology or medicine Nobelist Robert F. Furchgott, emeritus professor at S.U.N.Y. Downstate Medical Center in Brooklyn. We're sorry both for the omission and for having him bring up the rear of this column. SA

ILLUSTRATION BY MATT COLLINS; PHOTOGRAPH BY FRANK VERONSKY

ASK THE EXPERTS

How can global warming be traced to CO_2?

—J. Pope, Winston-Salem, N.C.

Pieter Tans, a senior scientist at the National Oceanic and Atmospheric Administration Earth System Research Laboratory, explains:

Although carbon dioxide is just a minor constituent of the atmosphere, it is one of the few atmospheric gases capable of trapping the heat radiating from the earth. At the earth's surface, visible radiation from the sun is absorbed, which causes heating. At the same time, the surface emits infrared radiation back to space, which produces cooling. (We cannot see infrared radiation, but we feel our skin absorbing it when we stand next to a hot stove.) The more sunlight is absorbed by the surface, the more radiation is sent out to space, until the heat loss to space equals the heat absorbed from the sun.

The gases that make up more than 99 percent of the atmosphere—nitrogen, oxygen and argon—do not absorb visible or infrared light and thus let both forms of radiation pass through untouched. The next most abundant gases, water vapor and CO_2, do absorb a portion of the infrared heat radiated by the earth, thereby preventing it from reaching space. This is known as the greenhouse effect, and without it our planet would very likely have a frozen surface, akin to that of Mars.

Even though carbon dioxide and water vapor make up a small amount of the atmosphere, those molecules share their absorbed heat with all the nitrogen, oxygen and argon molecules they bump into as they mix together. The atmosphere thus acts somewhat like a blanket that becomes more insulating when water vapor, CO_2 and other greenhouse gases increase.

The heating effect of extra carbon dioxide, methane, nitrous oxide and many other minor gases can be calculated with confidence based on properties that have been measured carefully in the lab. Currently the total heating produced by the increases of all such long-lived greenhouse gases (excluding water vapor) since preindustrial times is equal to about 1 percent of all solar radiation absorbed at the surface. The effect would be somewhat similar if the sun had started to shine 1 percent more brightly during the 20th century.

That may sound trivial, but small changes in the earth's heat balance can lead to large climatic changes—the ice ages and the warmer periods in between during the past several million years appear to have been separated by global average temperature differences of only about five degrees Celsius in the tropics and eight degrees C in polar regions. SA

For a complete text of this answer and others from scientists in diverse fields, visit www.sciam.com/askexpert

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MATT COLLINS