The Undeniable Case for Global Warming (*see page 64*)

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Hungry Shark's ELECTRIC SENSE
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How tiny twitches preserve vision and reveal thoughts

WINDOWS ON THE MIND

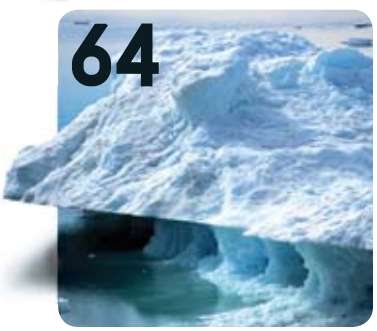
Racial Medicine
The Weak Science behind Ethnic Drugs

New Crops
Altered Roots for Future Farming

Wildfires
Predict and Control Dangerous Blazes

FEATURES

SCIENTIFIC AMERICAN August 2007 ■ Volume 297 Number 2

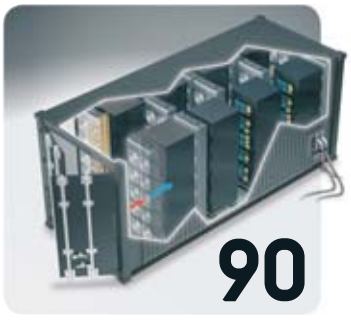


ON THE COVER

Cover photograph of eye by Jens Nieth, zefa/Corbis; photograph of shark by Stephen Frink, Getty Images.

SCI AM

Video simulations of how eyes make small, fast fixational movements to maintain our sense of vision are animated in every sense of the word. Watch them online at **www.SciAm.com/ontheweb**



SCI AM

Altered Crops: Your Thoughts?

Post your opinion of efforts to create new perennial crops on our editors' blog. Go to **www.SciAm.com/ontheweb**

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FORTRESS ISLAND OF TYRE (*below*) withstood the siege of Alexander the Great for seven months in 332 B.C. Geo-archaeologists recently solved the mystery of how Alexander's engineers were able to build a long causeway connecting the mainland to the island in order to finally conquer it.

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Find that answer and these other features at **www.SciAm.com/ontheweb**

On the Brink

Ten species that could go extinct in the next 10 years.

Podcast: Mark Twain—Fossil Hunter and Science Writer

Twain had a fascination for paleontology, technology and science in general.

Blog: Rooftop Solar

How 66 beer bottles equal one cheap solar water heater.

News: Putting a Price Tag on Death

Economists say balancing the pain of loss with the right amount of money could lead to more rational court awards.

Strange but True: Helmets Attract Cars to Cyclists

Safety gear has a perverse effect.

DAVID KERKHOFF (*camel*); MARK WEISS (*rhino*); ANDREA GINGERICH (*sea turtles*); MATT MATTHEWS (*iStockPhoto (Chinese alligator)*; GETTY IMAGES (*helmet*)

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DEPARTMENTS

LANDESGENDARMERIEKOMMAND FÜR TIROL/AUSTRIA

JACQUELINE GODANY

Little Black Pills

Race-based drugs are both promising and perilous

Race is one of the most inflammatory, slippery, maddeningly paradoxical concepts to afflict human consciousness; witness its ugly history. Shamefully, perversions of biology, anthropology and psychology have at various times racially justified colonialism, slavery and disenfranchisement. Medicine's own intersections with concepts of race have tended to be horrible as well: the grotesque Nazi experiments and the notorious Tuskegee studies of syphilis spring to mind.

Looking to change that awful record for the better is the drug BiDil, approved in 2005 to reduce the toll of congestive heart failure specifically among African-Americans. BiDil is not a product of research on the human genome, but researchers in the field of pharmacogenomics are combing our DNA for clues to new therapies—and better ways to match them to appropriate groups of patients. Because investigators will inevitably keep looking for correlations with racial groups, they will keep finding them. Thus, the era of race-based medicine dawns.

RACIAL Rx

The validity of race-based medicine ultimately depends on whether race is biologically meaningful and what that meaning is. The answers get murky. People of different races are genetically different—but so, too, are those of the same race. Differences in genetic traits, such as pigmentation, help to mark individuals' membership in races, but the genes involved vary so much within racial groups that effectively none of them reliably distinguishes the races on its own. Constellations of DNA sequences or genetic traits may be more common among certain ethnicities. But those populations often correspond only loosely to the broad racial categories in common use, which dilutes whatever physiological significance they might have had (Nigerians, Ethiopians and Jamaicans have distinct ancestries, but all get lumped together as black). Moreover, people routinely have forebears of different races, which makes a mockery of the silly rules for assigning them to racial groups. To a first approximation, then, race is biologically meaningless.

On the other hand, because societies do sort individuals into racial categories and treat them accordingly, race is far from meaningless with respect to sociology and public health. Bad environments arising from segregation and prejudice can be systematically hurtful. A society's history of racism can thereby lock medical risks into ethnic groups even in the absence of clear genetic differences.

Given the high rate of cardiovascular disease among African-Americans, any real remedy is one for which to be grateful. As law professor Jonathan Kahn recounts in "Race in a Bottle" (starting on page 40), however, BiDil's race-specific benefit was rather desperately teased out of studies on mixed populations, and it was not very large. Moreover, the strategy of marketing BiDil as a racial drug seems to have been developed to keep the combination of generic compounds in it under patent protection. It is hard not to be cynical about whether the drugmakers put profits ahead of prudence in a sensitive subject.

Even if BiDil is worth the distress of treading on racial sensibilities, future ethnic drugs may not be. As a society, we should know how to weigh the pros and cons. The situation will not always be black and white.

JOHN RENNIE *editor in chief*

FLYNN LARSEN (*Rennie*); AARON GOODMAN (*man in bottle*)

Among Our Contributors

R. DOUGLAS FIELDS
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National Institutes of Health
A neurobiologist trained in biological oceanography, his professional and personal enthusiasms range from neuronal plasticity to building guitars. This is his third article for *Scientific American*.

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Like her co-author Mark Finney, she is a developer of computer models used to predict wildfires throughout the U.S.

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Based in Washington, D.C., this accomplished journalist is the author of several books on computing and other subjects.

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Price of the Pump • Eye Scheme • Clever Birdies

APRIL 2007

"For automobiles running on hydrogen fuel to replenish their supplies, several thousand fueling stations would have to be built at the cost of billions of dollars."
—*James W. Armour, Jr.* VILLANOVA, PA.

Energy Economics

IN "GASSING UP with Hydrogen," Sunita Satyapal, John Petrovic and George Thomas write about the difficulties of storing hydrogen in automobiles to create a replacement for today's internal-combustion engines. Given the technical and economic challenges the authors describe, the targets they list for storage quantity and costs for 2010 and 2015 seem optimistic. But even if those targets are met, then what? For automobiles running on hydrogen fuel to replenish their supplies, several thousand fueling stations would have to be built at the cost of billions of dollars. Further, a new delivery infrastructure would have to be created to get hydrogen (or hydrogen precursors) to those stations.

Finally, where is the hydrogen to come from? Today most hydrogen is obtained from natural gas in a process that releases carbon dioxide. Hydrogen can also be made by electrolyzing water, but it takes lots of electrical energy to break hydrogen-oxygen bonds. If that electricity is obtained by burning coal, more carbon dioxide will be produced.

Tremendous investment over several decades would be needed to build a system to support a "hydrogen economy." A better approach would be to use currently available, affordable technology to triple the efficiency of gasoline-powered automobiles, which could fairly rapidly reduce the amount of oil needed to run those vehicles.

James W. Armour, Jr.
Villanova, Pa.

Rabbit's-Eye View

IN "THE MOVIES in Our Eyes," Frank Werblin and Botond Roska imply that the partial representations of natural scenes observed in a simulation of the rabbit retina are the same as those processed by the anatomically similar human retina. But the representations they show are quite blurry. A 1959 study of frog retinas by cognitive scientist Jerome Y. Lettvin and his colleagues showed that frogs cannot see stationary objects and concluded that their retinas are adapted to their needs. Rabbit and human needs differ, so we should expect their retinal processing to differ.

Martin B. Brilliant
Holmdel, N.J.

WERBLIN REPLIES: *It is correct that our representations of visual activity seem to lack fine detail; there are a few possible reasons why this is so. First, only humans and some primates have vision pathways in which a single cone photoreceptor connects to a single bipolar cell that connects to a single ganglion cell, and this likely does result in more acute vision than is possessed by other mammals.*

Second, it is most probable that higher visual centers of the brain use the information processed by the retina differently than the representations we included in our article. The figure labeled "Movie from cell type 1" on page 78, for example, represents information processed by a ganglion cell responsible for extracting the exact location of an object's edges. The inner boundary of the contour seen in this image is quite precise, and it is possible that higher visual centers would be able to increase its resolution.

Finally, we excluded from our descriptions a

number of other feature detectors within the retina that also contribute to the final combined representation sent to the brain. These include motion detectors and, in humans, a color-detecting system.

Corvid Company

IN "JUST HOW SMART *Are* Ravens?" Bernd Heinrich and Thomas Bugnyar suggest that young ravens' playful behavior with much larger carnivores teaches them how to get along with such animals, which provide them with much of their food.

Years ago I took home an injured raven, which I released once it had healed. The bird remained around our home during the fall and winter of that year, sharing food with our dog. In the fall, as the dog would doze in the sun, the raven would come up behind him and peck at his tail. The dog would growl and rise, and the bird would jump safely out of reach. After the dog moved off, the cycle would repeat.

During one winter night the temperature dived to −30 degrees Fahrenheit. I went outside to check on the raven. It was not on its usual roost near the front of the house. Somewhat concerned, I went to the back of the house to check on the dog. Pulling back the flap on our small doghouse, I peeked in and found them both, dog and raven, huddled together for warmth. When the cold spell passed, the two resumed their respectful distance.

IN THE COMPANY OF WOLVES: The need to dine out with larger predators may be a contributing factor to playfulness and intelligence in ravens.

JIM BRANDENBURG *Minden Pictures*

It seems to me that going into that unfamiliar, darkened doghouse would have run counter to instinct and must have involved some kind of reasoning ability that allowed the raven to envision consequence. The response testing of the dog that had gone on during the previous fall must have provided a basis for that logical process.

Grant W. Mason
Orem, Utah

Inborn Illness?

"SEEKING THE CONNECTIONS: Alcoholism and Our Genes," by John I. Nurnberger, Jr., and Laura Jean Bierut, focuses on studies seeking to pinpoint a genetic connection to alcoholism. Never has so much been spent to achieve so little for so many. Biological psychiatry has not changed a bit in the almost 20 years since I started residency, in that we always seem to be one important discovery away from insight. Despite decades of work and piles of "so what" research that have cost countless millions, we know no more of real substance about any so-called mental disorder. Loose associations with particular genetic loci are a meaningless goose chase. We do not need genetic studies to tell us people are predisposed to drinking too much nor gene chips to tell them to stop. I have seen thousands of alcoholics in my practice, and genetic profiles would not have fixed the developmental and social antecedents to their condition.

John Sorboro
Stow, Ohio

IN THEIR OTHERWISE informative and well-written article, Nurnberger and Bierut include the following statement: "Nobody gets to be alcohol-dependent without making some poor choices." Do these authors actually think that anyone has ever gotten up one morning and said: "I think I'll become an alcoholic today"? This is not any different from suggesting that someone might "decide" to become bipolar.

Alan Levine
Sonora, Calif.

Letters to the Editor

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Accident Epidemiology ▪ An Unsinkable Ship ▪ Truth Serum

Compiled by Daniel C. Schlenoff

AUGUST 1957

ROAD DATA—"Automobile accidents in the U.S. are now the subject of a large-scale investigation as if they were an epidemic—as they are. The Department of the Army, the American Medical Association and other major groups are studying many phases of the matter, from the design of tollbooths to the personality of truck drivers. Among other significant findings are that sedatives and tranquilizing drugs dull a driver's skill, and that the dangerous effects of an evening of drinking may last as long as 18 hours, regardless of coffee therapy."

STRESSING MICE—"The tranquilizing drugs are definitely what is needed for crowded living—at least for mice. Two workers from the Johns Hopkins Medical School cooped up groups of mice in canisters and gave half the groups Miltown [an early antianxiety drug], and the other half nothing. Half an hour later, they injected all the groups with a lethal dose of amphetamine. At the end of the experiment the untranquilized mice were all dead and the tranquilized ones were not even breathing hard."

AUGUST 1907

RMS *LUSITANIA*—"On a preliminary speed trial for the new turbine liner 'Lusitania' of the Cunard Line, the great ship easily reached a speed of 25 knots, and this in spite of the fact that her bottom was 'heavily coated with the chemically-saturated mud of the River Clyde.' The constructive features of the ship are novel, and because of her mammoth proportions are of unusual interest. The double bottom, covering the whole of the ship's length, is 5 feet in depth. There are nine decks in all, and the hull is divided into 175 separate watertight compartments, which, surely, establishes the claim that she is unsinkable by any ordinary disaster."

MECHANIZING AGRICULTURE: An early attempt from 1857

[EDITORS' NOTE: In 1915 the *Lusitania* was hit by a single torpedo fired from a German submarine and sank in 18 minutes.]

Find images of this ship from the article at **www.SciAm.com/ontheweb**

RADIOACTIVE DECAY—"Sir William Ramsay has recently made an announcement which, coming from so high a source, must be treated with respect. He states that after long experimenting with the effect of various combinations brought into contact with radium emanation [radon], he has observed that copper compounds are transmuted or 'degraded,' in his own words, to lithium. After a solution of copper phosphate has been treated with the emanation and the copper then removed, the spectrum of the residue exhibits the red line of lithium. The discovery, if substantiated, must certainly be regarded as one of the most brilliant chemical revelations of this radio-active age."

[EDITORS' NOTE: Copper does not decay into lithium; Marie Curie and Ellen Gleditsch suggested in 1908 that the lithium came from the glass containing the experiment.]

AUGUST 1857

FARMING—"Our illustration is a perspective view of a harvester invented by S. Gumaer, of Chicago, Ill. As the machine is moved forward by the horses, a connecting rod generates a peculiar and reciprocating motion in the cutters, and the straws are severed along the edges of the knives by an ordinary cutting action, like that of a scythe. The machine may be driven at any speed. Mr. G. estimates that the harvester can be afforded to the farmer at retail, ready for use, at $65."

LEGAL ETHER—"The process of etherization has been resorted to in Belgium as a means of acquiring judicial information. After a considerable robbery, two men were arrested and brought to trial. The former was condemned to hard labor for life, but in consequence of the latter pretending to be dumb and idiotic, his trial was postponed. It was found impossible to get even a sign of intelligence from him; but, on a medical investigation, he was etherized, and while under the effect of that application he spoke perfectly and in French. He was condemned to ten years' hard labor."

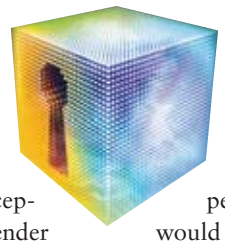
SCIENTIFIC AMERICAN, VOL. XII, NO. 51, AUGUST 29, 1857

Diabetes · Quantum Wiretap · No Prostate Help from Lycopene · Iceman Death

Edited by Philip Yam

Hack Job

Quantum cryptography has an uncrackable reputation [see "Best-Kept Secrets"; SciAm, January 2005]. A sender typically transmits a message encoded by polarized photons; anyone listening in would cause errors to appear in the reception, alerting the sender and receiver. Researchers at the Massachusetts Institute of Technology, however, show in the April 25 *Physical Review A* that quantum cryptography can be hacked, at least to a limited extent. They found a way to entangle the polarization of transmitted photons with the momentum of an eavesdropper's photon. By measuring the momentum, the eavesdropper could deduce the transmitted polarizations.



Quantum users can breathe easy, though: the trick works for only 40 percent of the data and would not be practical, because the setup requires that the eavesdropper use the same photon detector as the receiver.

Poking Out Lycopene

Lycopene, abundant especially in tomatoes, does not appear to prevent prostate cancer as once hoped (and hyped). Past studies had suggested that a diet rich in the antioxidant could protect against the disease, presumably because lycopene neutralizes free radicals, which are reactive molecules that can damage cells and DNA. In the latest study, a team led by researchers from the Fred Hutchinson Cancer Research Center in Seattle and the National Cancer Institute followed 28,000 men between the ages of 55 and 74. Lycopene and other antioxidants exerted no preventive effect, the scientists found. In fact, in a surprise, the team saw a positive correlation between one antioxidant, beta-carotene, and an aggressive form of prostate cancer. Look up the results in the May 2007 *Cancer Epidemiology, Biomarkers & Prevention*.

Pierced to Death

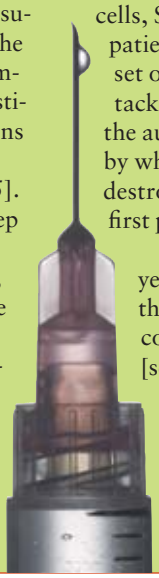
State-of-the-art CT scans appear to have identified the exact cause of death of Ötzi the Iceman, the famous 5,300-year-old glacier mummy found in the Tyrolean Alps [see "The Iceman Reconsidered"; SciAm, May 2003]. For years, researchers have wondered whether the arrowhead found in his back led to his demise, because people can survive with foreign objects in their bodies. An Italian-Swiss team reports that additional x-rays at the arrowhead site have revealed damage to an arterial wall, a pseudoaneurysm (an arterial bulge typically caused by trauma) and a hematoma—all signs that Ötzi lost massive amounts of blood. Writing online March 15 in the *Journal of Archaeological Science*, the researchers conclude "with almost complete certainty" that the Iceman bled to death shortly after being shot.

KENN BROWN (*quantum cube*); © PHOTO ARCHIVES OF THE SOUTH TYROL MUSEUM OF ARCHAEOLOGY (*Iceman*); GETTY IMAGES (*syringe*)

Transplants for Diabetes

Diabetics have dreamed of an injection-free cure, and for decades one great hope has been islet cell transplantation. But since 1974, only about 750 individuals with type 1 diabetes mellitus have received transplants of islets (derived from cadavers), which contain the insulin-producing beta cells, and very few of them achieved insulin independence beyond four years. The shortage of human islet cells and the immune response that rejects them have stifled the goal of making insulin injections obsolete [see "Treating Diabetes with Transplanted Cells"; SciAm, July 1995].

So researchers have begun to sidestep these issues by figuring out ways to transplant islet cells derived from pigs, which are in ample supply and produce insulin similar to that of humans. To hide the cells from immune attack, scientists are encapsulating them in a biocompatible semipermeable membrane. But the problem with encapsulation is that it prevents nutrients in the blood from getting to the islets, says Peter Stock, a transplant surgeon who heads the human islet cell program at the University of California, San Francisco. Hence, investigators still need to find a membrane that can obtain nourishment and repel immune cells.



Another way to increase the source of beta cells is with adult or embryonic stem cells, Stock points out. If derived from the patient's own body, such cells would not set off a transplant-rejecting immune attack. But stem cells may not get around the autoimmune response, the mechanism by which the body of a diabetes patient destroys insulin-making cells in the first place.

A cure for diabetes thus still seems years away. Novel procedures, such as those that encourage spleen cells to convert into beta cells, are promising [see "Putting Up with Self"; Insights, SciAm, December 2006]. And continuing advances in stem cell work—such as the transformation of adult skin cells into stem cells reported in the June 7 *Nature*—offer much hope. —*Thania Benios*

FOOD SAFETY

Protein Pretense

Cheating the standard protein tests is easy, but industry hesitates on alternatives BY ALISON SNYDER

After hundreds of dogs and cats fell ill this past spring, government officials traced the source to melamine, a nitrogen-rich compound found in plastics and fertilizer that, when ingested by the animals, crystallized in their kidneys and caused renal failure. The U.S. Food and Drug Administration later announced that producers may have deliberately added the compound to wheat gluten and rice protein concentrates to inflate the measured amount of protein. The greater the protein level in the concentrates, the higher the market price the products fetch. Regardless of whether its addition was deliberate or accidental, melamine snuck past standard industry protein analysis, suggesting that the century-old test methods should be reevaluated. Several alternatives exist, but the food industry has yet to make a switch.

NOT FIT FOR A DOG: Melamine added to pet food created false measures of protein content, fooling standard tests that look for nitrogen as a protein signal.

Traditionally, food protein is measured by a method developed by Danish brewer Johann Kjeldahl in the late 1800s. In this analytical technique, a strong acid digests a sample, breaking down the organic matter and releasing nitrogen, which is then converted to ammonia. The amount of ammonia indicates how much nitrogen was in the original sample and, hence, the amount of protein. This "proved to be a robust, precise method," says Julian McClements, a food scientist at the University of Massachusetts Amherst. It is attractive because it can be used for a variety of products and protein types. Another, similar nitrogen-based technique, called the Dumas test, is also popular with industry. It relies on burning the sample to release nitrogen. The Association of Analytical Communities (AOAC) International, a scientific association that sets standards for analytical methods, lists the Kjeldahl and Dumas techniques as the standard methods for measuring protein in food.

The nitrogen-based methods may be tried, but they are not entirely true. They assume that the source of all nitrogen in food is protein constructed from nitrogen-based amino acids. This assumption is reasonable if unadulterated food is being analyzed, because the other major components of food—carbohydrates and fats—do not contain nitrogen. But because the tests detect total nitrogen, from both protein and nonprotein alike, they do not truly measure protein.

Hence, any chemical rich in nitrogen can potentially trick the Kjeldahl or Dumas test. In the pet food scandal, nitrogen from melamine was indistinguishable from amino-acid nitrogen and contributed to the tally used to calculate the protein in the sample.

Several alternative, non-nitrogen-based protein tests exist, such as laboratory chromatography and ultraviolet spectrophotometry, but they are expensive and time-consuming and require extracting protein from food, a process that differs depending on the type of food. For rapidly analyzing food protein, "probably the best technique," McClements says, is infrared spectroscopy, which relies on the peptide bonds in proteins absorbing infrared light in distinguishable ways. The method demands that each chemical to be screened first be

LARRY WILLIAMS *Corbis*

run to calibrate the machine; if researchers are not looking for a particular chemical, they will not find it using infrared spectroscopy. The appearance of a nonprotein spike would indicate a possible contaminant in the sample that could then be identified through other tests.

The Canadian Grain Commission adopted near-infrared reflectance (NIR) technology, a type of infrared spectroscopy, for screening its grain supply some 30 years ago. Since then, the U.K., Australia, Russia and Argentina, among others, have also switched to NIR. More than 90 percent of wheat worldwide is screened with NIR, according to Phil Williams, a consultant at PDK Grain in British Columbia and an early adopter of the technology for use in the grain industry. In principle, NIR could measure protein in a variety of food types, including wheat gluten and rice protein concentrates.

Still, some doubt that NIR could economically replace the nitrogen-based tests. Carl Schulze, president of New Jersey Feed Lab, a Trenton-based company that analyzes food for industry, states that NIR works best when one type of feed is being tested repeatedly. But the high initial cost of setting up the machine and running samples that are similar to the products being tested means that the technique may not be a viable alternative for the independent laboratories that test the food supply.

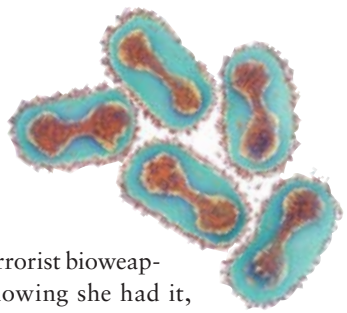
Thus far pet food makers and other processors have not decided whether to adopt new methods. "We're in the process of building a feed safety protocol," says Ron Salter, a vice president at feed distribution company Wilbur-Ellis in San Francisco. He adds that the company will be looking into feed sampling and testing procedures. In the meantime, nitrogen-based methods will likely remain top dog among protein-testing techniques.

Alison Snyder is based in New York City.

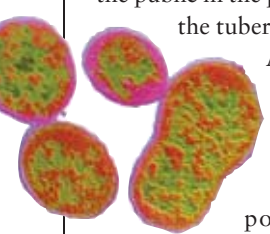
PUBLIC HEALTH

Laboratory Letdowns

Accidental infections in biosafety labs go unreported BY JOHN DUDLEY MILLER



Despite airtight double doors, disposable laboratory clothing, frequent decontamination and other precautions, accidental infections can happen at U.S. biological laboratories. Perhaps worse, though, is that accidents are going unreported. Although the U.S. has not confirmed any cases of sick scientists spreading their lab-derived infections to the public in the past 40 years, the case of the tuberculosis-carrying traveler Andrew Speaker shows that modern jet transportation could quickly spread deadly infections globally. Most important, the culture of nonreporting and lax enforcement of already weak incident-reporting regulations in the U.S. could make such secondary infections more likely. Indeed, some scientists believe they may have already occurred, as they have in other nations in which lab infections of smallpox, SARS, Marburg and H1N1 influenza viruses have spread to the general public.



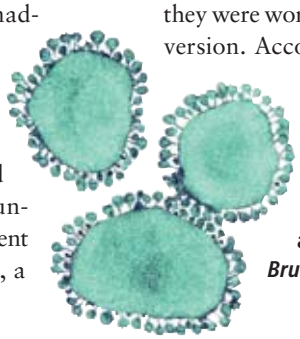
Research institutions would rather not face the blame and bad publicity associated with accidents, remarks immunologist Gigi Kwik Gronvall, a senior associate at the University of Pittsburgh's Center for Biosecurity. Instead many opt to hide their mistakes and hope that federal regulators do not find out.

According to a group of biosafety experts the center convened last summer, researchers do report accidents in biosafety level-four (BSL-4) labs, the highest level; such facilities study diseases that have no cure, so workers want to receive all available medical care. But accident reporting in BSL-3 and BSL-2 labs is much less laudable, these experts say. Because the diseases are less severe, scientists who catch them may not even realize that they acquired them from the lab.

In February 2006 at Texas A&M University, a student wearing inadequate protection while cleaning up in a BSL-3 lab contracted brucellosis. Rare in the U.S., the disease can infect both animals and people and may be fatal if untreated. The federal government classifies it as a select agent, a potential terrorist bioweapon. Not knowing she had it, the student stayed home sick for several weeks, enduring fevers and other flulike symptoms.

According to university records, when her own doctor diagnosed brucellosis two months later, she told Texas A&M, but the university waited a year to report the incident. It finally did so only under pressure from a bioweapons watchdog group, the Sunshine Project, which threatened to expose the accident if Texas A&M did not.

Sometimes lab mishaps occur because researchers think they are dealing with a different disease agent. In May 2004 two Boston University investigators were unknowingly infected with tularemia in a BSL-2 lab because they mistakenly believed they were working with a harmless altered version. According to B.U. officials, the



LAB INFECTIONS have occurred with (*clockwise from above*) the smallpox virus, the SARS coronavirus and the brucellosis bacterium, *Brucella abortus*.

CHRIS BJORNBERG *Photo Researchers, Inc.* (*smallpox*); LINDA STANNARD *UCT/Photo Researchers, Inc.* (*SARS*); CNRI *Photo Researchers, Inc.* (*Brucella abortus*)

two violated a policy requiring them to keep all tularemia samples under an enclosed box called a hood, which would have protected them. Both experienced flu-like symptoms and recovered.

The occurrence might have gone unnoticed—except that a third researcher with similar symptoms was hospitalized for several days in September 2004. Soon, other B.U. faculty members became suspicious that all three cases might have been tularemia, which blood tests confirmed. The university did not report the accident until November 2004, and it did not announce it publicly until January 2005.

Neither brucellosis nor tularemia typically spread from person to person, so the public probably was not exposed. But given the lack of reporting, no one knows whether similar incidents with more readily transmissible germs *have* infected outsiders. It "definitely is possible," says Richard Ebright, a biologist at Rutgers University. Microbiologist Patrick Bavoil of the University of Maryland agrees, saying that because researchers who do not know they are sick mingle with the public and because so many pathogens can be transmitted between individuals, "this must have happened already many times."

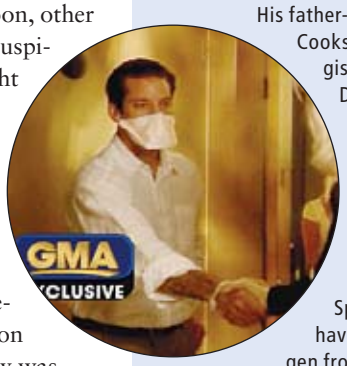
The one case that could well have transmitted disease among people was the March 2000 incident at the U.S. Army Medical Research Institute of Infectious Diseases (USAMRIID) in Fort Detrick, Md. There a microbiologist who worked on the bioweapon bacterium *Burkholderia mallei* in a BSL-3 lab came down with the disease it causes, glanders, which can be fatal. Despite a fever and swollen armpit glands, he kept coming to work for six weeks and never told the army he was sick. Finally, the researcher had to be hospitalized and put on a mechanical ventilator; he had a 104.5-degree fever and abscesses in his liver and spleen. Once physicians diagnosed glanders and treated it, he recovered. His commanding officer refused to punish him for not reporting his illness, citing medical privacy laws.

Part of the reason similar cases continue to go undocumented is that there are few federal reporting regulations, and many of them are not enforced, says the Sunshine Project's U.S. director Edward Hammond. To receive grants from the National Institutes of Health, universities must report all accidents, but they face no penalty for not reporting. Even though federal audits in 2006 showed that 21 of 25 universities inspected did not follow all the rules for handling select agents, none of them were punished for noncompliance. Accidents involving recombinant DNA techniques do not have to be reported to the NIH unless researchers deem them "significant." The Occupational Health and Safety Administration need not be notified, either, unless someone dies or three or more employees are hospitalized as inpatients.

To combat underreporting, Pitt's Center for Biosecurity recommends mandatory but nonpublicized reporting to the federal government of all accidents and near misses in BSL-3 and BSL-4 labs. Knowing what kinds of incidents occur most often, federal officials could then issue new requirements designed to prevent repeats. Although Hammond complains that not making such reports public would unfairly allow unsafe research institutions "to keep communities in the dark about dangers in their midst," Pitt's Gronvall counters that without anonymity, "people wouldn't report."

John Dudley Miller is based in Cleveland.

Traveling with TB



ABC NEWS' GOOD MORNING AMERICA

Atlanta lawyer Andrew Speaker, shown during an interview on ABC News' *Good Morning America,* took commercial trans-Atlantic flights while infected with an extensively drug-resistant (XDR) strain of tuberculosis. His case has raised several questions. One was whether he became infected because of a laboratory accident. His father-in-law, Robert C. Cooksey, is a microbiologist at the Centers for Disease Control and Prevention who studies the TB bacterium. In a statement, Cooksey said that tests show that he never had XDR-TB; therefore, Speaker could not have gotten the pathogen from him. Statistics published this past spring indicate that XDR-TB infections in the U.S. occur, if not commonly: 49 people contracted it between 1993 and 2006, and 23 of them were native-born. So the connection between Speaker's infection and Cooksey's job may be coincidental.

CONSERVATION

A Return on Redwoods

A novel deal may save forests and recoup investors BY MARK FISCHETTI

For years, special-interest groups have raised money to buy and rope off wild lands to protect them. But in June a unique partnership announced it had purchased 50,635 acres of northern California redwood forest and would preserve the land by operating it as a nonprofit business. The acquisition was funded entirely by private capital. The lead group, the Redwood Forest Foundation, Inc. (RFFI), in Gualala, Calif., claims the deal creates the first nonprofit working forest in the country and could be a model for safeguarding other natural resources.

"It's always difficult to get the first

transaction done," says Don Kemp, executive director of RFFI and architect of the arrangement. "I'm hoping this one will be a catalyst for others."

RFFI purchased the parcel, which is known as the Usal Redwood Forest, for $65 million, which it borrowed from Bank of America at a reduced rate. The tract had been logged for decades, but the latest operator, Hawthorne Timber Company, was seeking a buyer because it had harvested the most profitable parts of the woods. The remaining "inventory" comprises mostly young trees that must grow for many years before becoming economically attractive. In similar situations, owners typically sell the land to developers who build on it, or the state buys the land and turns it into a preserve or park. Kemp, a former head of capital markets for the Bank of New York, says that although the latter approach is admirable, it consumes public dollars, eliminates jobs and takes the land off the tax rolls.

Those downsides, he says, are making it less feasible to protect land by trying to stop all activity on it. The RFFI deal "provides a significant public interest. We're cutting the rate of tree harvest way down, to less than 2 percent. We're sustaining recreation. Meantime our objective is to rehabilitate the redwood forest back to its natural state, which could take 100 years." The light logging, recreation and restoration, he notes, will preserve local jobs as well as trees. "We're continuing employment, and we're contributing taxes."

JUSTIN BAILIE *Aurora Photos*

TREE HUGGING: A new financial approach to sustaining forests could make investors and conservationists smile.

Environmental and business interests are watching the initiative as a test case for whether the free market can promote conservation. Kemp says the traditional model—wherein groups such as the Nature Conservancy buy a piece of land and cordon it off—is becoming harder to achieve because of limited donor money and because shutting down land can reduce employment for area residents.

The RFFI approach treats the Usal Forest, which is 180 miles north of San Francisco, as an economically sustainable

property. "Our investors are very patient; they will get their money, but over 15 years or more," says Kemp, who credits its proponents within Bank of America who offered the lesser interest rate because of the environmental benefits and the good public relations value. "I was disappointed in some of the so-called green investors," he adds, "who wanted 9 percent or more, or equity."

To recoup some of the purchase cost, RFFI will sell a coastal part of the forest, about 300 acres, for use as a park. It will also negotiate the sale of a conservation easement across the remaining acreage with the Conservation Fund, an environmental group based in Arlington, Va., which will protect the land should the nonprofit structure fail at any time. The Campbell Group, a forest management company in Portland, Ore., will oversee the property under guidelines RFFI has designed.

Some environmentalists and conservationists remain skeptical, saying RFFI will end up having to sell off more land to stay afloat or to satisfy investors. Kemp acknowledges that it will take a decade or more to know if the forest can indeed sustain itself economically.

If so, the approach might offer a new model for conserving with private financing any natural resource that can be valued as a tangible asset, such as a freshwater lake. A few similar attempts have relied in part on public money; in July 2006, for example, a partnership that included the Nature Conservancy, Conservation Forestry, and private and state conservation funds purchased the Wild River Legacy Forest in northeastern Wisconsin from International Paper. The 64,600 acres of land will also host sustainable logging.

Both approaches will be needed to save forests as lumber companies increasingly look to sell off harvested land. "It's not like every acre will be turned into condos," says Tom Tuchmann, president of U.S. Forest Capital, LLC, which brokered the RFFI deal. "Nevertheless, many owners are cutting up their land and parceling it out." He is already pursuing a transaction akin to the RFFI deal with the Deschutes Basin Land Trust in Bend, Ore., for the 33,000-acre Skyline Forest there.

Tuchmann maintains that the RFFI model could work elsewhere in the country and the world. The two primary conditions for success, he says, are "a community-based buyer that understands the biological potential of the property and the economic needs of an investor. And parties that are willing to set aside historic biases toward one another to achieve forest preservation and economic goals."

ENERGY EFFICIENCY

On the Rebound

Discouraging people from using more energy just because it costs less BY LINDA BAKER

Economics 101 states that if prices decline, consumption will increase. Now economists are applying this law of demand to policies intended to improve energy efficiency and reduce greenhouse gas emissions linked to global warming. The result is called the rebound effect, and it takes place when higher consumption undercuts the energy savings produced by a given technology.

For example, a household that saves energy and money by installing better insulation may then decide it can afford to raise the thermostat during the winter. "If you invoke a program or policy that lowers the cost, people do more of that thing," remarks Richard Newell, an energy and environmental economist at Duke University.

Although most experts accept the existence of the rebound effect, the debate continues over its magnitude. Two recent studies reveal different quantitative results but also point to a consensus regarding the best way to adjust for the human tendency to use more when costs are less. In the context of climate change, the superior instrument appears to be a tax on carbon emissions.

This past January economists at the University of California, Irvine, published an article in *Energy Journal* examining the rebound effect for motor vehicles—that is, the extent to which fuel-efficiency standards will encourage people to drive more. They used vehicle mileage data in the U.S. from 1966 to 2001 to estimate a rebound effect for motor vehicles of about 10 percent. That is, for a given decrease in the cost of driving, the number of miles driven would increase by 10 percent of that change.

Although the effect has declined as incomes have increased, rising gas prices have partially offset that decline: study coauthor Kurt Van Dender recalibrated the model using 2006 gas prices and found that a 58 percent increase in fuel costs increases the rebound effect from 10 to 15 percent once people switch to more efficient vehicles. Overall, however, "we find that the rebound effect is quite small," says Van Dender. "If you go ahead and regulate fuel economy, you will indeed reduce fuel consumption by a pretty large amount."

Another study, published in the January *Energy Economics,* points in a different direction. Economists at Umeå University in Sweden used national consumption data for transportation, food, heating and other goods to evaluate how an increase in energy efficiency—modeled as a price reduction—would influence consumption in each of these sectors. For example, the model showed that a 20 percent rise in heating efficiency would boost demand for car transportation by 4.2 percent. Overall, increasing energy efficiency by 20 percent at the macroeconomic level would actually raise a country's carbon emissions by 5 percent.

"Fuel efficiency also reduces fuel consumption in our model, but the point is that we then use the money on something else that may be very carbon-intensive," coauthor Runar Brännlund says. "We fool ourselves if we think improving efficiency by 20 percent means emissions go down 20 percent." To compensate for the rebound effect, energy efficiency must be coupled with other policy solutions to lower emissions, Brännlund says: "We have to jack up the price of carbon." Hefty taxes would be one way to do that. In Sweden, to reduce the carbon emissions to their original level, policymakers would have to increase the nation's carbon tax—in existence since 1991—by 130 percent.

Brännlund notes that the European Union is now considering a new fuel-economy standard. Some U.S. legislators are trying to raise mileage standards as well, although automakers are battling those efforts. In a "politically constrained" environment, Van Dender argues, fuel-economy regulation is "not so bad." But basic economics states that demand responds to price. "If there is a social cost attached to gasoline consumption that consumers do not take into account when they burn gasoline, then it's very hard to arrive at any other conclusion than a gasoline or carbon tax," Brännlund says. And even a small rebound effect can "have a really big social cost," Van Dender adds, worsening air pollution and traffic congestion.

PAY LESS, DRIVE MORE: People will use more energy if it costs less. Researchers are only beginning to quantify this effect as it relates to carbon emissions.

ISTOCKPHOTO

Linda Baker is based in Portland, Ore.

GENETICS

Attitude Screen

Seeing if the public is ready for personal genetic information BY CHRISTINE SOARES

A chance to peek into the future—at least one possible future—is always a tempting fantasy. But if it were offered in reality, would you take it? And if you didn't like what you saw, how hard would you try to change it? After almost 20 years spent reading, mapping and analyzing human DNA, researchers at the National Human Genome Research Institute (NHGRI) believe that personal genetic information is nearly ready for use by consumers in managing their health, so the institute is launching a large-scale study to gauge whether consumers are ready for the information.

The year-long Multiplex Initiative will ultimately involve thousands of subjects, who will be offered a personal genetic report card based on screening for gene variations associated with increased risk for major diseases. The investigators are interested in how many take up the offer, why, and how participants respond to their results. The researchers also hope to gain insights into the best ways for health professionals to communicate information about genetic risk.

"Our major outcomes and measures are going to be … do they understand the tests, because this is hard stuff to package for the general public," explained senior investigator Lawrence Brody of the NHGRI's Genome Technology branch, when announcing the initiative in early May in Washington, D.C., "and whether or not they find the test useful, what are their attitudes about it?"

The investigators are recruiting among members of the Henry Ford Health System, a Detroit-area HMO, and will follow up with participants to see if learning their genotype prompts them to seek out wellness programs or change any behaviors.

As many as 10,000 potential participants between the ages of 25 and 40 will be receiving mailed invitations to be screened for versions of some 15 genes associated with higher risk for developing major conditions such as type 2 diabetes, coronary artery disease, osteoporosis, lung cancer, colorectal cancer, and melanoma.

WHAT ARE THE CHANCES? Gene variations can indicate higher risk for developing future illness, but the information is less concrete than a formal diagnosis.

By mid-June, about 70 people, or 20 percent of the recipients who responded to the first wave of invitations, had signed on to be tested, according to the lead investigator, Colleen M. McBride, chief of the NHGRI's Social and Behavioral Research branch. "That's about what we expected," she says. "These are young, healthy individuals.… They are the best target population for prevention, but it's hard to get on their radar screen." Her goal is to have 1,000 people tested over the coming year.

"I think the NHGRI study is very valuable," says Catherine Schaefer, the lead investigator of a larger Kaiser Permanente research project that is currently recruiting among the 3.5 million members of that California HMO. Schaefer is gathering DNA samples and other health information in the hope of discovering new gene variants that confer disease risk or protection. One of her group's challenges is explaining to potential participants the importance of understanding even small genetic influences on complex diseases and the ways they might suggest interventions. The influence of most known susceptibility variations "is really quite modest," she says. "It's very important to learn how people respond to this very complex genetic information." Indeed, the NHGRI's study was prompted in part by McBride's own doubts about whether personal genomics was ready for consumers.

In the past, genetic testing has been mostly limited to single-gene diseases, such as Huntington's or cystic fibrosis, where the grim association between genotype and eventual illness is clear and certain. Conditions such as diabetes, in contrast, might involve the activity of hundreds or thousands of genes in different aspects or stages of the disease, and diet or other environmental factors may also interact with those genes over a lifetime. The statistical association between a variant gene and increased risk of developing diabetes may therefore be clear, but it is far from the entire picture.

"For better or worse, we've convinced the public that genetics is very important and deterministic," Brody explained. "And now we have to back off of that a little bit."

All the conditions included in the Multiplex Initiative screening are preventable,

CJPG/ZEFA/CORBIS (*photograph*); JOHNNY JOHNSON (*photoillustration*)

so participants can decide for themselves whether the results are worth acting on. Current measures of future risk typically rely on symptoms that have already appeared, such as high blood pressure or spinal degeneration, noted NHGRI director Francis Collins during the announcement. Genetic testing, he said, "has the potential of moving the timetable back to an earlier point so that you can begin to practice prevention before you're already half in the grave."

PHYSICS

Dimensional Shortcuts

Is there evidence for string theory in a neutrino experiment? BY MARK ALPERT

The neutrino is the oddball of particle physics. It has no charge and rarely interacts with other particles, but it comes in three flavors—electron, muon and tau—and madly oscillates from one flavor to the next as it travels along. For the past five years, researchers at the Fermi National Accelerator Laboratory in Batavia, Ill., have been firing beams of muon neutrinos at the MiniBooNE detector, a huge spherical tank filled with 800 tons of mineral oil, to see how many of the particles changed in flight to electron neutrinos. The first results, announced in April, mostly vindicated the Standard Model—the conventional theory of particle physics—but an unexplained anomaly in the data leaves open a more exotic possibility. Some scientists speculate that the cause of the anomaly is a new kind of neutrino that can take shortcuts through the extra dimensions predicted by string theory.

BOON FOR NEUTRINOS: A researcher examines the photomultiplier tubes that detect the flashes of light from neutrino interactions.

PETER GINTER

The impetus behind MiniBooNE was to follow up a previous experiment, conducted at Los Alamos National Laboratory in the 1990s, which had shown evidence for a fourth type of neutrino. Called the sterile neutrino, this putative particle would be even more elusive than the three ordinary flavors because it would not be subject to the weak nuclear force as the other particles are but would interact only through gravity. Because the existence of sterile neutrinos would challenge the Standard Model, researchers were eager to run a similar experiment to confirm or refute the findings. The results from MiniBooNE, however, were a mixed bag. For neutrinos with energies ranging from 475 million to three billion electron volts, the number of flavor oscillations nicely matched the Standard Model predictions, but at lower energies investigators found a significant excess of electron neutrinos.

Even stranger, three physicists had anticipated this result. Their work is an outgrowth of string theory, which stipulates the existence of at least 10 dimensions to create a framework that incorporates both gravity and quantum mechanics. To explain why we do not perceive the extra dimensions, string theorists have posited that all the ordinary particles in our universe may be confined to a four-dimensional "brane" floating within an extra-dimensional "bulk," like an enormous sheet of flypaper suspended in the air. But certain special particles can travel in and out of the brane, notably the graviton (which conveys the gravitational force) and the sterile neutrino. In 2005 Heinrich Päs, now at the University of Alabama, Sandip Pakvasa of the University of Hawaii and Thomas J. Weiler of Vanderbilt University proposed that if the brane is curved or microscopically deformed, then sterile neutrinos could take shortcuts through the bulk. These shortcuts would influence the flavor oscillations, increasing the probability of a transition at certain energies.

As it turned out, MiniBooNE's results closely tracked the predictions made by Päs, Pakvasa and Weiler. Several researchers involved in the experiment were so struck by the similarity that they sent congratulatory e-mails to the three theorists. "It is indeed startling to see how well your model appears to fit our excess of low-energy events!" wrote Bill Louis, co-spokesperson for the MiniBooNE team. Because scientists have found no experimental evidence for string theory so far, confirming the existence of extra dimensions would indeed be a major breakthrough.

Physicists caution that the similarity could simply be nothing more than a spooky coincidence. The MiniBooNE researchers are now trying to determine whether background effects or faulty analysis could have skewed their count of electron neutrinos. In the meantime, Päs and his colleagues are refining their theory. "Our solution seems to be a little speculative at first glance," Päs admits. "But I think it is absolutely legitimate to discuss possible scenarios that can explain the excess, should it be confirmed."

ROBOTICS

Playing It by Ear

A machine-listening system that understands three speakers at once BY TIM HORNYAK

Prince Shotoku was a seventh-century politician attributed with authorship of Japan's first constitution. Famed as a nation builder, he is said to have been able to listen to many people simultaneously, hearing the petitions of up to 10 supplicants at once and then handing down judgments or advice.

Inspired by the legendary prince, Japanese researchers have spent five years developing a humanoid robot system that can understand and respond to simultaneous speakers. They posit a restaurant scenario in which the robot is a waiter. When three people stand before the robot and simultaneously order pork cutlet meals or French dinners, the robot understands at about 70 percent comprehension, responding by repeating each order and giving the total price. This process takes less than two seconds and, crucially, requires no prior voice training.

Such auditory powers mark a fundamental challenge in artificial intelligence—how to teach machines to pick out significant sounds amid the hubbub. This is known as the cocktail party effect, and most machines do not do any better than humans who have had a few too many martinis. "It's very difficult for a robot to recognize speakers in a noisy environment," says Hiroshi G. Okuno of Kyoto University, the team leader and a pioneer in the field. Reverberations, extraneous sounds and other signal interruptions also pose difficulties.

Indeed, the era of easy natural-language communication with machines, a dream batted around at least since the time of Alan Turing, seems far off for the everyday user. A humorous example: Microsoft's live demo last year of the Windows Vista speech-recognition feature, which mangled the salutation "Dear Mom" and a verbal attempt to fix an error, producing "Dear Aunt, let's set so double the killer delete select all."

NOW HEAR THESE: Hiroshi G. Okuno poses with Robovie R2 and SIG2, machines that can comprehend several speakers at once.

In comparison, Okuno's system is remarkably accurate and does not require speakers to wear a headset (unlike commercial speech-recognition programs), because the microphones are embedded in a robot. His so-called machine-listening program performs what is known as computational auditory scene analysis, which incorporates digital signal processing and statistical methods. It first locates the sources of the audio and then separates the sounds with computational filters. The next step is key: automatic missing-feature mask generation. This powerful technique masks auditory data, such as cross talk, that the system decides are unreliable as it tries to zero in on a particular speaker. The system then compares the processed information with an internal database of 50 million utterances in Japanese to figure out which words were spoken. When the filtered version of each speaker is played back, only a few sounds from the other speakers are audible.

The result is a robust robot listener that is closer to the human brain's auditory powers than other systems. Okuno says it might handle as many as six talkers depending on their relative angles and the number of microphones utilized (currently eight). The robot can move and orient toward speakers, too, thereby enhancing performance.

"Okuno's project for robots that can understand overlapping voices does a really nice job of combining the best ideas in multimicrophone source localization with the powerful technique of missing-feature speech recognition," remarks Dan Ellis, head of Columbia University's Laboratory for the Recognition and Organization of Speech and Audio. "What makes his work stand out from anything else is the commitment to solving all the practical problems that come up in a real-world deployment … and making something that … can enable a robot to understand its human interlocutors in real-world situations."

Besides serving up fast food, Okuno's robot could lead to a hearing prosthesis that is just as good at reducing noise interference. Such a device could be combined with a sophisticated automatic paraphrasing system, which would be more important because hearing-impaired people rely heavily on context in conversation, Okuno thinks. Okuno himself is nearly deaf without hearing aids after years of listening to loud music through headphones. "The current hearing capabilities of humanoid robots are similar to mine," he chuckles.

Okuno expects much wider applications. "In the near future, many appliances will have microphones embedded in them," he predicts—and will do a lot more than ask if you want fries with that.

Tim Hornyak is author of Loving the Machine: The Art and Science of Japanese Robots, published in 2006.

TIM HORNYAK

PSYCHOLOGY

Roots of Science Hatred

Adults may resist scientific facts because of childhood experiences. Yale University psychologists note that before children can even speak, they develop commonsense assumptions about the physical world that can persist into adulthood and clash with scientific discoveries. For instance, because objects fall down if not held up, kids may have trouble accepting the world is round, reasoning that things on the other side should naturally fall off. Intuitive notions concerning psychology also lead children to see everything as designed for some reason—for example, a cloud's purpose might be to rain—which can lead to opposition to evolution. In reporting their work in the May 18 *Science*, the researchers also note that when both adults and kids obtain knowledge from others, they judge claims based on how much they trust the source of an assertion. It suggests that science will meet exaggerated resistance in societies where alternative views are championed by trustworthy authorities, such as political or religious figures. —*Charles Q. Choi*

BIOPHYSICS

Quantum Photosynthesis

A long-standing mystery of photosynthesis is how the process converts sunlight with nearly 100 percent efficiency to chemical energy. The key may be quantum coherence, the same phenomenon that makes lasers and superconductors work. Researchers at the University of California, Berkeley, investigated purple bacteria, where an ensemble of pigments and proteins absorbs light and channels its energy into chemicals. Components of this complex oscillate after they get excited with light, and these excitations are kept synchronized by specific vibrations of the protein connecting these components, like well-timed pushes on a swing to keep it in motion. This coherence makes the ensemble act together as a "supermolecule" of sorts, rapidly settling on the most efficient energy pathway. The research, in the June 8 *Science*, could improve designs for solar cells and other synthetic light-harvesting devices. —*Charles Q. Choi*

KONRAD WOTHE *Minden Pictures (photograph);* MATT COLLINS *(illustration)*

Data Points

Healthy Investing

In an aging U.S. in which the younger generation starts work later, maintaining the labor force means that people need to work well past the age of 65. A team led by Kenneth G. Manton of Duke University argues that the nation should dramatically increase research to boost longevity of the workforce and to lower age-associated health costs. Using economic and demographic data, the group has calculated ideal amounts for the U.S. to invest in biomedicine.

Projected U.S. population in 2034: **375 million**

Number who will be 65 years or older: **75 million**

Optimal level of annual biomedical investment as a percent of gross domestic product: **12.8**

Expressed as an amount in today's economy: **$1.6 trillion**

Current U.S. investment: **$360 billion**

Economic value of increased life span, 1970–2000: **$95 trillion**

Value after removing health care expenditures: **$60 trillion**

Annual percent decrease in disability for those 65 and older, 1982–2004: **1.5**

Expressed as a number who did not become disabled: **2.7 million**

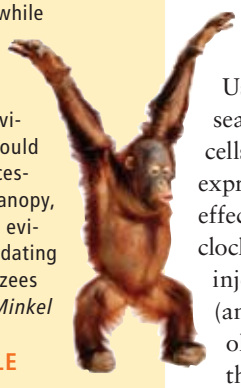
Medicare dollars saved if trend continues to 2034: **$810.2 billion**

SOURCES: U.S. Census Bureau; Proceedings of the National Academy of Sciences USA *online, June 15*

In Brief

UPRIGHT BEHAVIOR

Our two-legged life may have originated in the trees, say researchers who spotted numerous instances of wild Sumatran orangutans walking in the trees. In some 90 percent of those instances, the apes walked with straight legs while using their hands to maintain balance. This simian sauntering suggests that, contrary to previous thinking, bipedalism could have begun before our ancestors descended from the canopy, which would explain fossil evidence of upright behavior dating back from before chimpanzees and humans split. *—JR Minkel*



SOAKING THE MANTLE

Water under the earth's crust helps to generate volcanic activity and lubricate rock, possibly triggering large earthquakes, but how water made it under the crust was uncertain. Scientists at the University of Tokyo used a seismic array to investigate the Japan Trench. Water exists in the oceanic crust as hydrated minerals, which are expected to expel their water at the pressures and temperatures found 50 to 150 kilometers deep. Instead of floating upward, this freed water could fuse with mantle rock to form greenish serpentinite and get subducted downward below the crust. The researchers found what appears to be a channel of such hydrated rock flowing down farther into the mantle on top of a descending plate, confirming how the mantle gets wet. The findings are slipped into the June 8 *Science*. *—Charles Q. Choi*

PARLEZ-VOUS ENGLISH, BABY?

Visual cues alone seem to enable infants to recognize when a multilingual person switches dialects. Researchers at the University of British Columbia assert that without hearing a word, a four-month-old child can detect a language shift simply by observing shapes made by the speaker's mouth and other facial changes. Cultural mannerisms such as rhythmic head bobbing can also cue the babies. Infants in a monolingual family seem to lose this innate capacity by the age of eight months. *—Nikhil Swaminathan*

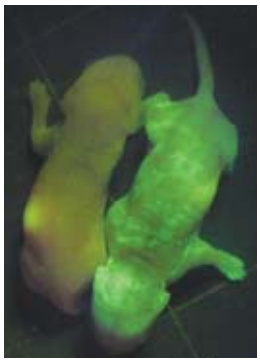
STEM CELLS

New Ways for More Stem Cells

Two methods may dramatically increase the availability of embryonic stem cells. Using biochemical techniques, three independent teams reprogrammed mouse skin cells into cells nearly indistinguishable from the embryonic kind. Using a virus as the messenger, the researchers inserted into adult mouse skin cells four key genes that are expressed in embryonic cells, effectively turning back the clock on the skin cells. When injected into a blastocyst (an embryo just a few days old), they contributed to the development of its layers—and mixed in with the mature animals' germ cells.

These findings, reported online June 6 by *Nature* and in the June 7 issue of *Cell Stem Cell*, build on past work of a team led by Shinya Yamanaka of Kyoto University, which had created more limited reprogrammed cells. Researchers may know in the next year whether the process works in human cells.

The June 7 issue of *Nature* also describes a method to derive stem cells from single-celled fertilized embryos, or zygotes; previously, many scientists believed that only unfertilized eggs would do. Instead of removing a zygote's nucleus, a separate Harvard University group swapped the chromosomes of an adult cell for those of the zygote before its nucleus re-formed during cell division. The approach yielded harvestable stem cells as well as mouse clones. Fertilized zygotes, which are routinely discarded at in vitro fertilization clinics, are more abundant than unfertilized eggs. *—JR Minkel*

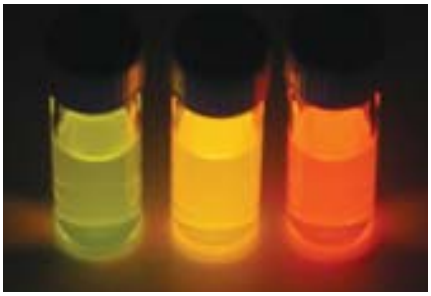


MOUSE EMBRYOS grew from reprogrammed skin cells tagged with a fluorescence gene.

PHYSICS

Catch the Laser Rainbow

Semiconductor specks called nanocrystals may be pointing the way to lasers that shine in colors beyond the basic red and blue seen in bar-code scanners and DVD players. Semiconductors create laser light by offering electrons a choice of two energy states, lower or higher. The wavelength of light emitted depends on the band gap, or difference in energy between states, which in nanocrystals decreases with size, says Victor Klimov of Los Alamos National Laboratory. Klimov and his colleagues slashed the energy needed to make nanocrystals lase by wrapping zinc selenide around cadmium sulfide cores, producing crystals four to 20 nanometers wide. Lasers made from such two-layer nanocrystals could be cheaper and more efficient than today's semiconductor versions, which consist of layered stacks at least several microns thick. See the May 24 *Nature* for more illumination. *—JR Minkel*



RAINBOW BRIGHT: Semiconductor nanocrystals glow in varying colors depending on the size of the crystals.

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CATHERINE LEDNER *Getty Images (orangutan)*; FROM "*IN VITRO* REPROGRAMMING OF FIBROBLASTS INTO A PLURIPOTENT ES-CELL-LIKE STATE," BY M. WERNIG ET AL., IN *NATURE* ONLINE; JUNE 6, 2007 *(mice)*; SERGEI IVANOV *Los Alamos National Laboratory (nanocrystals)*

SciAm Perspectives

Worse Than Gasoline

Liquid coal would produce roughly twice the global warming emissions of gasoline

BY THE EDITORS

Lawmakers of both parties are proposing amendments to the so-called energy independence bill that would massively subsidize the coal industry to produce liquid coal as a replacement for foreign oil. (The admirable original bill is designed to increase fuel efficiency in cars and light trucks, encourage production of biofuels, and provide funds to develop technology that will capture carbon dioxide emissions from power plants.)

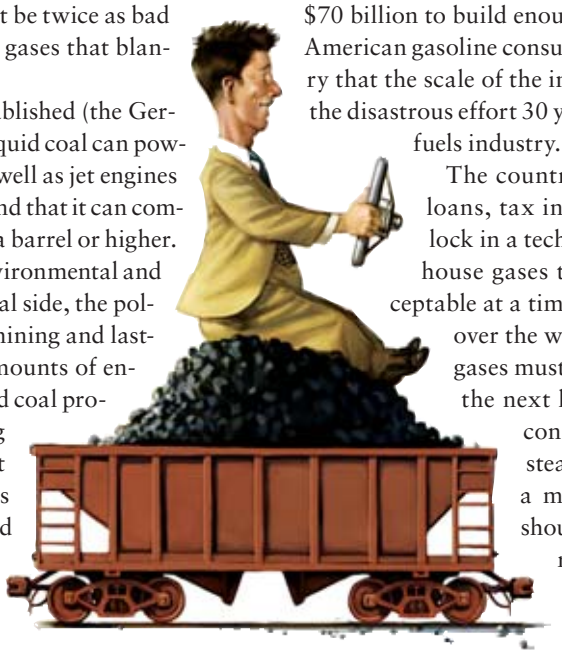
Senator Jeff Bingaman, Democrat of New Mexico, opposed big subsidies for coal-based fuels until mid-June, when he moved to offer up to $10 billion in loans for coal-to-liquid plants. At the same time, Senator Barack Obama, from coal-rich Illinois, abruptly shifted his support for subsidizing coal-derived fuel production to concentrate on another bill he had been sponsoring that would cut greenhouse gas emissions and reduce carbon content in transport fuel.

The shifting positions of Bingaman and Obama underscore the tension between efforts to reduce dependence on foreign oil and to slow global warming. Liquid coal—produced when coal is converted into transportation fuel—would at best do little to rein in climate change and would at worst be twice as bad as gasoline in producing the greenhouse gases that blanket the earth and lead to warming.

The conversion technology is well established (the Germans used it during World War II), and liquid coal can power conventional diesel cars and trucks as well as jet engines and ships. Coal industry executives contend that it can compete against gasoline if oil prices are $50 a barrel or higher. But liquid coal comes with substantial environmental and economic negatives. On the environmental side, the polluting properties of coal—starting with mining and lasting long after burning—and the large amounts of energy required to liquefy it mean that liquid coal produces more than twice the global warming emissions as regular gasoline and almost double those of ordinary diesel. As pundits have pointed out, driving a Prius on liquid coal makes it as dirty as a Hummer on regular gasoline.

One ton of coal produces only two barrels of fuel. In addition to the carbon dioxide emitted while using the fuel, the production process creates almost a ton of carbon dioxide for every barrel of liquid fuel. Which is to say, one ton of coal in, more than two tons of carbon dioxide out. Congressional and industry proponents of coal-to-liquid plants argue that the same technologies that may someday capture and store emissions from coal-fired plants will also be available to coal-to-liquid plants. But even if the carbon released during production were somehow captured and sequestered—a technology that remains unproven at any meaningful scale—some studies indicate that liquid coal would *still* release 4 to 8 percent more global warming pollution than regular gasoline.

Liquid coal is also a bad economic choice. Lawmakers from coal states are proposing that U.S. taxpayers guarantee billions of dollars in construction loans for production plants, guarantee minimum prices for the new fuel, and guarantee big purchases by the government for the next 25 years. Their mantra is that coal-based fuels are more American than gasoline. But no operating coal-to-liquid plants exist in the U.S., and researchers at the Massachusetts Institute of Technology estimate it will cost $70 billion to build enough plants to replace 10 percent of American gasoline consumption. Some energy experts worry that the scale of the incentives could lead to a repeat of the disastrous effort 30 years ago to underwrite a synthetic fuels industry.



MATT COLLINS

The country would be spending billions in loans, tax incentives and price guarantees to lock in a technology that produces more greenhouse gases than gasoline does. This is unacceptable at a time when leading scientists from all over the world are warning that greenhouse gases must be cut by at least 60 percent over the next half a century to avert the worst consequences of global warming. Instead of spending billions to subsidize a massively polluting industry, we should be investing in efficiency and in renewable energy technologies that can help us constrain global warming today. ■

Sustainable Developments

Making Development Less Risky

Innovative forms of insurance could unshackle a green revolution in Africa and other poor nations

BY JEFFREY D. SACHS

BRUCE GILBERT/EARTH INSTITUTE

Life at the bottom of the world's income distribution is massively risky. Poor households lack basic buffers—savings accounts, health insurance, water tanks, diversified income sources, and so on—against drought, pests, disease and other hazards. Even modest shocks, such as a temporary dry spell or a routine infection, can be devastating.

These risks have knock-on effects. To take one prime example, the expected economic return on the use of fertilizer is very high in Africa, yet impoverished farmers cannot obtain it on credit because of the potential for a catastrophic loss in the event of a crop failure. Their households cannot bear the risk of a loan, and so they remain destitute. Managing risk is therefore important not only for smoothing out the well-being of these farmers over the years but also for enabling their escape from extreme poverty.

Traditional crop insurance is almost nonexistent in Africa.

For these reasons and others, financial risk management is likely to come to the forefront of strategies for poverty reduction. Microfinance has already introduced markets for the poor. Microinsurance and other kinds of risk management will likewise yield important tools.

Traditional crop insurance is almost nonexistent in Africa for several reasons. Suppose a company tried to sell a crop insurance policy to a peasant farmer with a one-acre farm. A standard policy would specify payments in the event of measured crop losses from specified hazards (such as drought, pests and temperature extremes), and would require an actuarial model of applicable

risks and the completion of a contract. Payments would occur only after the verification of losses and (usually) of the underlying adverse events.

Multiple problems would be fatal to such a policy: the absence of an actuarial risk model; adverse selection (farmers with especially risky conditions would seek the contracts); moral hazard (farmers covered by insurance might fail to take other protective measures); and the enormously high relative costs of marketing, signing and assessing losses.

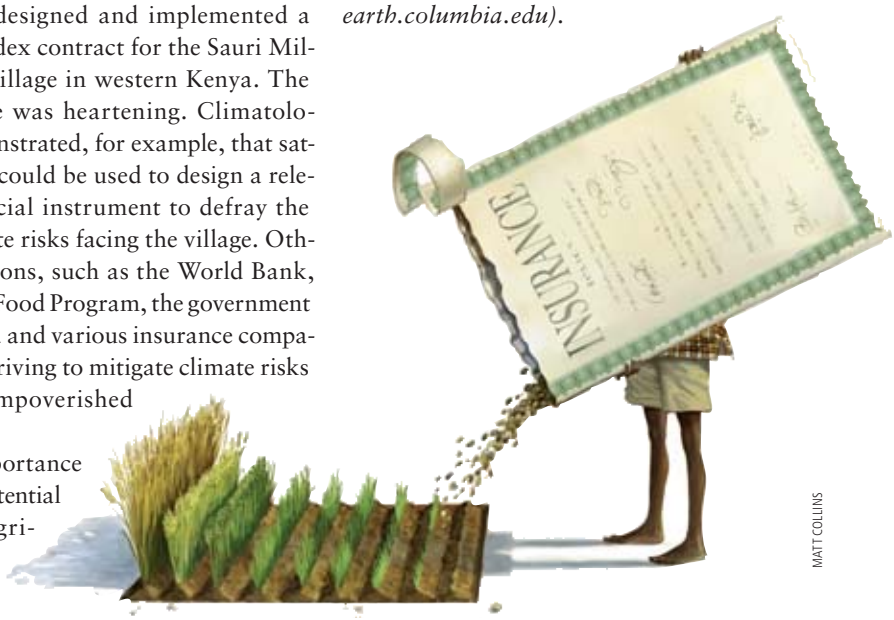
Two huge innovations are correcting these weaknesses. First, instead of insuring a farmer's actual crop losses, a policy can diversify much of a farmer's risk by creating a financial derivative, such as a weather-linked bond that pays in the event of a seasonal drought, dry spell or other adverse shock. A weather station or satellite can observe a drought objectively, eliminating the need to examine outcomes on individual farms. Moral hazard and adverse selection are irrelevant, because the price of the "drought bond" depends on the objective probabilities of measurable weather shocks, not on the behaviors of an individual farmer.

The second key strategy is to combine the weather-linked bonds with other financial services to the farmer. For example, a bank could make a seasonal loan to a cooperative of hundreds or thousands of farmers for the mass purchase of fertilizers and high-yield seeds, with the loan repayment due to be reduced or waived in the event of a drought and the repayment schedule calibrated to the drought's extent. The bank, in turn, would buy a weather-linked bond to insure itself against such a dry spell.

Earlier this year the Earth Institute at Columbia University and the reinsurer Swiss Re designed and implemented a rainfall-index contract for the Sauri Millennium Village in western Kenya. The experience was heartening. Climatologists demonstrated, for example, that satellite data could be used to design a relevant financial instrument to defray the high climate risks facing the village. Other institutions, such as the World Bank, the World Food Program, the government of Ethiopia and various insurance companies, are striving to mitigate climate risks in other impoverished regions.

The importance of—and potential for—an agricultural breakthrough is critical for Africa's future. Its farmers do not produce enough food to feed a hungry continent. Yet existing technologies could enable them to do so, if the financing were arranged. Africa's green revolution is therefore likely to be accompanied by a supportive African financial revolution that brings state-of-the-art risk management techniques to bear on behalf of some of the world's poorest people. ■

Jeffrey D. Sachs is director of the Earth Institute at Columbia University (www.earth.columbia.edu).



MATT COLLINS

Skeptic

Bad Apples and Bad Barrels

Lessons in Evil from Stanford to Abu Ghraib

BY MICHAEL SHERMER

The photographs of prisoner abuse from Abu Ghraib shocked most Americans. But social psychologist Philip Zimbardo had seen it all 30 years before in the basement of the psychology building at Stanford University, where he randomly assigned college students to be "guards" or "prisoners" in a mock prison environment. The experiment was to last two weeks but was terminated after just six days, when these intelligent and moral young men were transformed into cruel and sadistic guards or emotionally shattered prisoners.

As he watched the parade of politicians proclaim that Abu Ghraib was the result of a few bad apples, Zimbardo penned a response he calls the Lucifer Effect (also the title of his new book from Random House), namely, the transformation of character that leads ordinarily good people to do extraordinarily evil things. "Social psychologists like myself have been trying to correct the belief that evil is located only in the *disposition* of the individual and that the problem is in the few bad apples," he says.

BRAD SWONETZ

But, I rejoin, there *are* bad apples, no? Yes, of course, Zimbardo concedes, but most of the evil in the world is not committed by them: "Before we blame individuals, the charitable thing to do is to first find out what situations they were in that might have provoked this evil behavior. Why not assume that these are good apples in a bad barrel, rather than bad apples in a good barrel?"

How can we tell the difference? Compare behavior before, during and after the evil event in question. "When I launched my experiment at Stanford, we knew these students were good apples because we gave them a battery of tests and every one of them checked out normal," Zimbardo explains. "So, on day one they were all good apples. Yet within days the guards were transformed into sadistic thugs and the prisoners were emotionally broken." Likewise at Abu Ghraib. Zimbardo notes that before going to Iraq, Staff Sergeant Ivan "Chip" Frederick—the military police officer in charge of the night shift on Tiers 1A and 1B, the most abusive cell blocks at Abu Ghraib—"was an all-American patriot, a regular churchgoing kind of guy who raises the American flag in front of his home, gets goose bumps and tears up when he listens to our national anthem, believes in American values of democracy and freedom, and joined the army to defend those values."

The guards were transformed into sadistic thugs, and the prisoners were emotionally broken.

Before Abu Ghraib, Frederick was a model soldier, earning numerous awards for merit and bravery. After the story broke and Frederick was charged in the abuses, Zimbardo arranged for a military clinical psychologist to conduct a full psychological assessment of Frederick, which revealed him to be average in intelligence, average in personality, with "no sadistic or pathological tendencies." To Zimbardo, this result "strongly suggests that the 'bad apple' dispositional attribution of blame made against him by military and administration apologists has no basis in fact." Even after he was shipped off to Fort Leavenworth to serve his eight-year sentence, Frederick wrote Zimbardo: "I am proud to say that I served most of my adult life for my country. I was very prepared to die for my country, my family and friends. I wanted to be the one to make a difference."

Two conclusions come to mind. First, it is the exceedingly patriotic model soldier—not a rebellious dissenter—who is most likely to obey authorities who encourage such evil acts and to get caught up in believing that the ends justify the means. Second, in *The Science of Good and Evil*

(Owl Books, 2004), I argued for a dual dispositional theory of morality—by disposition we have the capacity for good and evil, with the behavioral expression of them dependent on the situation and whether we choose to act. Aleksandr Solzhenitsyn, who knew a few things about the capacity for evil inside all of our hearts of darkness, explained it trenchantly in *The Gulag Archipelago:* "If only there were evil people somewhere insidiously committing evil deeds, and it were necessary only to separate them from the rest of us and destroy them. But the line dividing good and evil cuts through the heart of every human being. And who is willing to destroy a piece of his own heart?" ■

MATT COLLINS

Michael Shermer is publisher of Skeptic *(www.skeptic.com). His latest book is* Why Darwin Matters *(Henry Holt, 2006).*

THE EDITORS' BLOG

www.SciAm.com/blog

ROCK FESTIVAL AS HUMAN EXPERIMENT: HIP-HOPPING FOR SCIENCE

What would happen if all 1.3 billion Chinese jumped in unison?

Umm … nothing, really.

That's the deduction from an experiment carried out today with tens of thousands of human lab rats who attended the German music festival Rock at the Ring. The idea of enlisting rock-crazed youths to advance geological science got started when the creators of a science program on German television asked themselves what would happen if the entire Chinese population engaged in synchronized hopping.

They saw Rock at the Ring as an opportunity to provide an answer to that question on a microcosmic scale. At the concert (total attendance 50,000), the band We Are Heroes cued the masses of rock fan/hoppers with drumbeats to go airborne, while the program's crew recorded the event on videotape and the Potsdam Geological Research Center recorded it on seismometers.

A producer of the science program, Quarks & Co., characterized the "gang boing" as a "mini-mini earthquake," according to a news report from radio Deutsche Welle. A seismometer measured four oscillations per second, while the earth moved only $^1/_{20}$ of a millimeter. "We showed that people cannot start a (real) earthquake by hopping," remarks Ulrich Grünewald, producer of the program, who emphasized the difficulty of getting tens of thousands of people to synchronize their jumps.

Maybe just stick to the Wave.

Posted by Gary Stix, June 4, 2007

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Forum

Have Brain, Must Travel

A successful space exploration program requires astronauts as well as robots

BY JIM BELL

MAUREEN BELL

These are incredibly exciting times for space exploration. NASA currently operates more than 50 robotic spacecraft that are studying Earth and reaching throughout the solar system, from Mercury to Pluto and beyond. Another 40 unmanned NASA missions are in development, and space agencies in Europe, Russia, Japan, India and China are running or building their own robotic craft. With such an armada at our disposal, delivering a stream of scientific data from so many distant ports, you might think that researchers like me who are involved in robotic space exploration would dismiss astronaut missions as costly and unnecessary. To the contrary: many of us embrace human exploration as a worthy goal in its own right and as a critically important part of space science in the 21st century.

Although astronaut missions are much more expensive and risky than robotic craft, they are absolutely critical to the success of our exploration program. Why? Because space exploration is an adventure—a *human* adventure—that has historically enjoyed broad public support precisely because of the pride we take from it. President John F. Kennedy committed the U.S. to sending astronauts to the moon to make a statement about the power of democracy and freedom, not to do science. As a by-product, some outstanding lunar science was done, leading ultimately to an understanding of the moon's origin. What is more, the Apollo moon program trained and inspired an entire generation of researchers and engineers, who made the breakthroughs that paved the way for robotic missions, as well as much of the tech-

nology that we take for granted today.

Letting the Apollo program end prematurely was a phenomenal mistake. NASA's subsequent strategy for human exploration, focused on space shuttle missions and orbital space stations, turned out to be uninspiring and tragically flawed. The recent successes of the Mars rovers, the Cassini probe to Saturn and other robotic missions may signal a renaissance, but the situation is still precarious. Indeed, the post-Apollo decline in public interest in space exploration reverberates today in the debates over NASA's budget and the general skepticism about the agency's future relevance, especially among the generation now entering the workforce. Further triumphs of the robotic missions will be possible only if public and political interest is rebuilt and sustained by a reinvigorated program of human exploration.

What is more, human brains will be vitally needed in many future missions. Although robots have proved their worth in documenting and measuring the characteristics of distant places, they fall far short of humans when it comes to making judgments, incorporating broader contexts into decision making and learning from their experiences. Some of these capabilities can be programmed, and so-called machine learning has advanced considerably in the past few decades. But the neural complexity that is so often needed to make discoveries—the same combination of logic, experience and gut instinct required to solve a mystery—cannot easily be distilled to a series of "if-then" statements in a computer algorithm. Robotic brains will lag far behind in these kinds of abilities for a long time to come, perhaps forever, thus placing severe constraints on the science they can do on other planets.

Robotic craft have worked well for the first age of space exploration, when simply flying a probe past a planet or landing on an alien terrain was enough to make dramatic discoveries. That era, however, is coming to an end. Now we are entering a new age of space exploration in which we must look more carefully at such planetary landscapes, as well as at what lies underneath them—analyzing the rocks, soils and gases of distant worlds in greater detail to flesh out the history of our solar system. This kind of science absolutely requires human explorers. In this new era, we will need brave people with brains to boldly go where no robot can take us. ■

Jim Bell is an astronomer and planetary scientist at Cornell University and scientific leader of the Pancam team for the Mars Exploration Rover mission. His recent book, Postcards from Mars, *showcases some of the vistas of the Red Planet obtained by robotic eyes.*

MATT COLLINS

THE EDITORS' BLOG

www.SciAm.com/blog

NEVER MIND THE CONSENSUS. DOWN WITH VACCINES!

Global warming and evolution, meet vaccines. The scientific community seems to be largely aligned on all of your sides: exists and needs to be dealt with; no controversy to be taught; and doesn't cause autism.

That won't stop the U.S. judicial system from being plagued by claims that what scientists have found through careful study is incorrect.

Apparently a school board in Chesterfield County, Virginia, is ordering new textbooks, and it's feeling the heat from community members who want books with a few extra pages on intelligent design.

On Monday the U.S. Court of Federal Claims will host lawyers representing one of 4,800 children living with autism, whose families have filed claims alleging that vaccines are the causal culprit. This despite the release by the Institute of Medicine, a part of the National Academies, of eight reports over three years on the subject. The final word was that there is no link between autism and vaccines (specifically, measles-mumps-rubella and others that contained the mercury-containing compound thimerosal)....

Paul Offit, chief of infectious diseases at Children's Hospital of Philadelphia and a co-inventor of a vaccine for rotaviruses, wrote a sort of pre-elegy to vaccines in the *Boston Globe*.... "Vaccine makers removed thimerosal from vaccines routinely given to young infants about six years ago; if thimerosal were a cause, the incidence of autism should have declined. Instead the numbers have continued to increase. All of this evidence should have caused a quick dismissal of these cases...."

Posted by Nikhil Swaminathan, June 8, 2007

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Anti Gravity

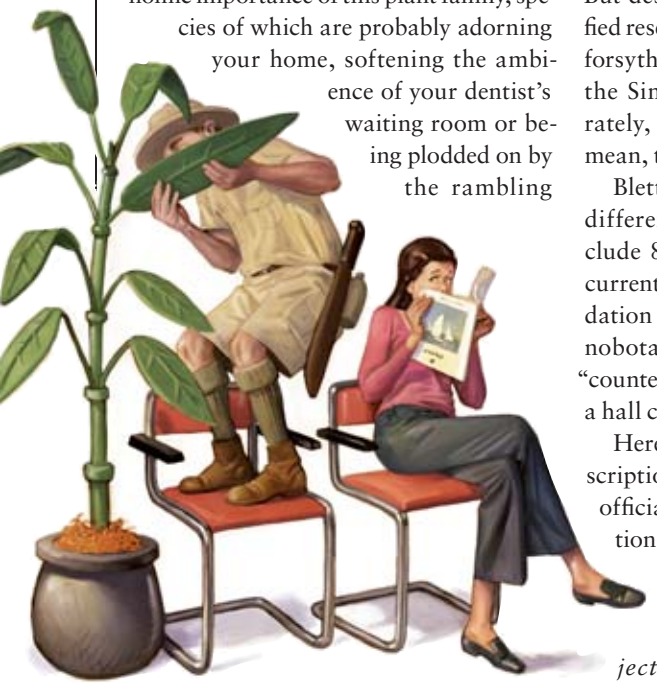
Floral Derangement

Some of these vegetables are minerals

BY STEVE MIRSKY

The late Harvard University paleontologist Stephen Jay Gould said that every species designation represents a theory about that organism—the species assignment is more than a mere naming; it is a classification of the organism within the context of all the other creeping, crawling, clinging and cavorting life on earth. As such, the discovery of a charismatic new species of animal or plant often piques the interest of both the scientific community and the lay public. Finding an entirely new genus is even more exciting. So it is somewhat shocking that a peer-reviewed publication announcing the discovery of a previously uncharacterized *family* of plants—an even higher taxonomic level than genus—has gone virtually unnoticed.

The shock intensifies when one considers the incredible ubiquity and great economic importance of this plant family, species of which are probably adorning your home, softening the ambience of your dentist's waiting room or being plodded on by the rambling behemoths of your local football team.



Fortunately I received a copy of the manuscript describing the plant family in question from one Nat Bletter, the lead author of the paper, which appeared online recently—April 1, oddly enough—in the journal *Ethnobotany Research and Applications*. The journal article's title says it all, albeit obtusely: "Artificae Plantae: The Taxonomy, Ecology, and Ethnobotany of the Simulacraceae."

As the authors note, the family Simulacraceae represents more than a "technical curiosity": it is "a genuine scientific conundrum." Individuals appear to be virtually immortal, they easily form not just interspecies but intergeneric crosses, and they lack any genetic material. (Had Mendel chosen a species from this family for his genetics research, the rules and chemistry of heredity might remain unknown to this day, along with Mendel.) But despite previous disregard by qualified researchers, the plastic peonies, fabric forsythia and wax watermelon wedges of the Simulacraceae live—or, more accurately, exist—among us at every fern. I mean, turn.

Bletter and his co-authors describe 17 different genera of phony flora that include 86 species, samples of which are currently stored at New York City's Foundation for Artificial Knowledge and Ethnobotany (what's a four-letter word for "counterfeit"?), which does double duty as a hall closet.

Here is the journal article's formal description of the new family in Latin, the official language of taxonomic designation. Although the Latin in this case is a bit porcine: "Simulacraceae—*away andbray ewnay antplay amilyfay omposedcay ofway objectsway ademay ybay umanshay* (How you doing so far, uddybay?) *otay ooklay ikelay anyway eciesspay inway ethay ingdomkay Antaeplay orway ancifulfay eciesspay avinghay omponentscay ofway away ivinglay antplay* (I always thought it was antwork and grasshopperplay) *eciesspay orway away ombinationcay ofway omponentscay omfray everalsay ivinglay antplay eciesspay utbay otnay ookinglay exactlyway ikelay anway extantway antplay.*" Similar swiny Pliny language describes each genus. And the authors note that because there existed absolutely no previously published taxonomic research about this family, "we did not have to coerce any unpaid students to do any literature searches."

In his spare time, Bletter is a graduate student at the International Plant Science Center at the New York Botanical Garden. He notes that his intensive research on the Simulacraceae stemmed from SCADS—severe chronic avoidance of dissertation syndrome. "We are not sure if SCADS is genetic or environmentally transmitted," he says, "but perhaps that's the subject of our next huge NIH-funded project."

Simulacraceae include the genus *Plasticus,* fake plants "typically composed primarily of complex polymers of long-chain hydrocarbons, indicative of their origins in the petrochemical industries"; the genus *Calciumcarbonatia,* faux vegetation designed out of seashells; the genus *Paraffinius,* familiar examples of which are the dust-covered wax bananas, grapes and apples in the big bowl on Grandma's kitchen table; and the genus *Silicus,* which includes the truly world-renowned collection of some 3,000 individual specimens of glass flowers, representing more than 830 real flower species, housed at Harvard's Museum of Natural History. Now there's some intelligent design. ■

PHOTOGRAPH BY FLYNN LARSEN; ILLUSTRATION BY MATT COLLINS

Race in a Bottle

Drugmakers are eager to develop medicines targeted at ethnic groups, but so far they have made poor choices based on unsound science

By Jonathan Kahn

KEY CONCEPTS

- BiDil, a drug that combats congestive heart failure by dilating the arteries and veins, was approved in 2005 as a treatment for African-Americans only.
- There is no firm evidence that BiDil works better for African-Americans than for whites.
- BiDil is a combination of two generic pills that are available at one-sixth the cost of the patented drug.
- Although BiDil may delay hospitalization and death for heart failure patients, the race-specific approval of the drug sets an unwise precedent.

—The Editors

Two years ago, on June 23, 2005, the U.S. Food and Drug Administration approved the first "ethnic" drug. Called BiDil (pronounced "bye-dill"), it was intended to treat congestive heart failure—the progressive weakening of the heart muscle to the point where it can no longer pump blood efficiently—in African-Americans only. The approval was widely declared to be a significant step toward a new era of personalized medicine, an era in which pharmaceuticals would be specifically designed to work with an individual's particular genetic makeup. Known as pharmacogenomics, this approach to drug development promises to reduce the cost and increase the safety and efficacy of new therapies. BiDil was also hailed as a means to improve the health of African-Americans, a community woefully underserved by the U.S. medical establishment. Organizations such as the Association of Black Cardiologists and the Congressional Black Caucus strongly supported the drug's approval.

A close inspection of BiDil's history, however, shows that the drug is ethnic in name only. First, BiDil is not a new medicine—it is merely a combination into a single pill of two generic drugs, hydralazine and isosorbide dinitrate, both of which have been used for more than a decade to treat heart failure in people of all races. Second, BiDil is *not* a pharmacogenomic drug. Although studies have shown that the hydralazine/isosorbide dinitrate (H/I) combination can delay hospitalization and death for patients suffering from heart failure, the underlying mechanism for the drug's efficacy is not fully understood and has not been directly connected to any specific genes. Third, and most important, no firm evidence exists that BiDil actually works better or differently in African-Americans than in anyone else. The FDA's approval of BiDil was based primarily on a clinical trial that enrolled only self-identified African-Americans and did not compare their health outcomes with those of other ethnic or racial groups.

So how did BiDil become tagged as an ethnic drug and the harbinger of a new age of medicine? The story of the drug's development is a tangled tale of inconclusive studies, regulatory hurdles and commercial motives. BiDil has had a relatively small impact on the marketplace—over the past two years, only a few million dollars' worth of prescriptions have been sold—but the drug has demonstrated the perils of using racial categories to win approval for new phar-

maceuticals. Although African-Americans are dying from heart disease and other illnesses at younger ages than whites, most researchers believe the premature deaths result from a complex array of social and economic forces [see "Sick of Poverty," by Robert Sapolsky; Scientific American, December 2005]. Some medical professionals and policy experts, however, have pointed to BiDil as proof that genetic differences can explain the health disparity. Worse, some pharmaceutical companies are now using this unfounded argument to pursue other treatments targeted at various ethnic groups, a trend that may segregate medicine and fatten the profits of drugmakers without addressing the underlying causes that are killing so many African-Americans before their time.

Birth of BiDil

The BiDil saga began more than 20 years ago with a pair of studies designed to gauge the effects of vasodilating drugs—which widen blood vessels—on heart failure, a debilitating and ultimately fatal disease that afflicts millions of Americans. Until then, doctors treated heart failure with diuretics (to reduce the accumulation of fluid that results from inadequate pumping) and digoxin (to increase the contraction of the heart muscle) but had little else at their disposal. In the early 1980s Jay Cohn, a cardiologist at the University of Minnesota, hypothesized that administering two vasodilators, hydralazine and isosorbide dinitrate, might ease the strain on weakened hearts by relaxing both the arteries and veins. Together with the U.S. Veterans Administration, Cohn designed and conducted two trials to assess this theory.

The first Vasodilator Heart Failure Trial (V-HeFT I) tested the H/I combination against a placebo and a drug called prazosin, which is used to treat high blood pressure. The results seemed to show great promise for the combination. The second trial, V-HeFT II, tested H/I against enalapril, a first-generation angiotensin-converting enzyme (ACE) inhibitor. (ACE inhibitors lower blood pressure by curbing the production of vessel-constricting peptides.) As it turned out, enalapril proved more effective than H/I for treating heart failure. From that point forward, ACE inhibitors became the new first-line therapy for heart failure patients. Doctors began recommending hydralazine and isosorbide dinitrate—both available as inexpensive generic pills—for those who did not respond well to ACE inhibitors.

▲ **APPROVAL of BiDil as a treatment for congestive heart failure in African-Americans has encouraged drugmakers to consider developing other medicines targeted at racial or ethnic groups. But most scientists agree that these categories are not useful for predicting drug responses, because the genetic variation among individuals in the same race is much greater than the variation between races.**

PHOTOILLUSTRATION BY AARON GOODMAN; JEN CHRISTIANSEN (*pills*)

[BUYING TIME]

Milestones in the Development of BiDil

1986 The results of the first Vasodilator Heart Failure Trial (V-HeFT I) are published. The combination of hydralazine and isosorbide dinitrate (H/I) shows promise.

1987 Jay Cohn of the University of Minnesota applies for a patent on the method of using hydralazine and isosorbide dinitrate together. BiDil is born.

1991 A second trial, V-HeFT II, shows that enalapril, an ACE inhibitor, is more effective than H/I for treating heart failure.

1996 Cohn and Medco, which holds the patent rights to BiDil, bring the drug to the FDA for approval.

FIRST PATENT

Cohn, however, remained committed to developing a treatment that combined hydralazine and isosorbide dinitrate because he believed in its effectiveness. In 1987 he applied for a patent on the *method* of using the drugs together to treat heart failure in all people, regardless of race. (He could not get a patent on the drug combination itself because both medicines were already available in generic form.) He then licensed the patent rights to Medco, a small pharmaceutical firm in North Carolina, which took steps in the early 1990s to put the H/I combination into a single pill—and BiDil was born.

Medco and Cohn brought BiDil to the FDA for approval in 1996. In early 1997 the agency refused to approve the drug. Ironically, most of the doctors on the FDA's review panel thought BiDil did in fact work and said they would consider prescribing it. The problem was not with the drug but with the statistical data from the V-HeFT trials, which were designed not to meet the regulatory standards for FDA approval but to test the hypothesis that vasodilators could treat heart failure. After the rejection, Medco's stock plummeted by more than 20 percent, and the company let the patent rights revert to Cohn. By 1997 half of the 20-year life of the original BiDil patent had already passed, which may explain Medco's reluctance to sink more money into the drug.

BiDil's Racial Rebirth

It was only at this point that race entered the story. After the FDA's rejection of BiDil, Cohn went back to the V-HeFT results from the 1980s and broke down the data by race, examining how well African-Americans had responded to the competing treatments. Such retrospective "data dredging" can yield useful insights for further investigations, but it is also fraught with statistical peril; if the number of research subjects in each category is too small, the results for the subgroups may be meaningless. Cohn argued that H/I worked particularly well in the African-Americans enrolled in the V-HeFT studies. The clearest support for this claim came from V-HeFT I, which placed only 49 African-Americans on H/I—a tiny number considering that new drug trials typically enroll thousands of subjects. In 1999 Cohn published a paper in the *Journal of Cardiac Failure* on this hypothesized racial difference and filed a new patent application. This second patent was almost identical to the first except for specifying the use of H/I to treat heart failure in black patients. Issued in 2000, the new patent lasts until 2020, 13 years after the original patent was set to expire. Thus was BiDil reinvented as an ethnic drug.

Race-specific patent in hand, Cohn relicensed the intellectual-property rights to NitroMed, a small Massachusetts firm. The FDA then gave NitroMed the go-ahead to conduct the African-American Heart Failure Trial (A-HeFT), a relatively small study involving 1,050 self-identified African-Americans. In A-HeFT, half the heart failure patients took BiDil while the other half received a placebo; at the same time, the patients in both groups continued taking their already prescribed treatments for heart failure (for example, about 70 percent of the subjects in both groups were on ACE inhibitors). The results were strikingly positive: the mortality rate in the BiDil subjects was 43 percent lower than that in the placebo group. In fact, BiDil appeared so effective that A-HeFT's Data Safety Monitoring Board suspended the trial early, in July 2004, so that the drug could be offered to the subjects in the placebo group as well. NitroMed's stock surged on the news, more than tripling in value in the following days. The next June the FDA formally approved BiDil with a race-specific label, indicating that it was for use in black patients.

But researchers have good reason to believe

[THE AUTHOR]

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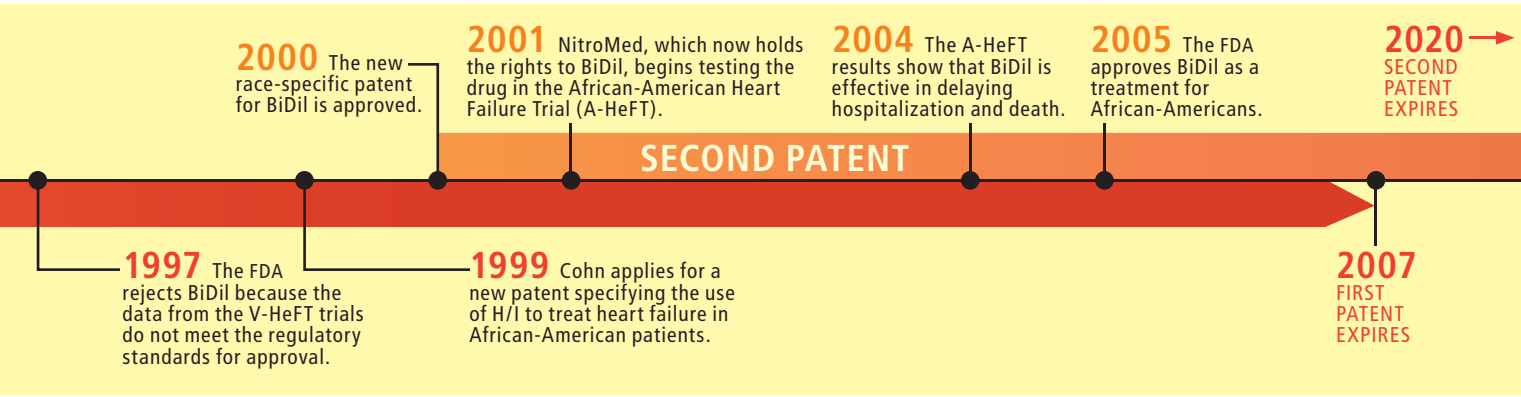
COURTESY OF HAMLINE UNIVERSITY (*Kahn*); JEN CHRISTIANSEN (*pills*)



that BiDil would also be effective in nonblack patients. Indeed, Cohn himself has said he believes the drug should work in people of all races. So why did the developers of the drug test it in only one ethnic group? The answer seems to be driven more by commerce than by science. If the FDA had approved BiDil for the general population, the patent protection for the drug's manufacturer would have expired in 2007. Restricting the clinical trial to African-Americans maximized the chances that the FDA would approve the race-specific use of BiDil, giving NitroMed an additional 13 years to sell the H/I combination without competition.

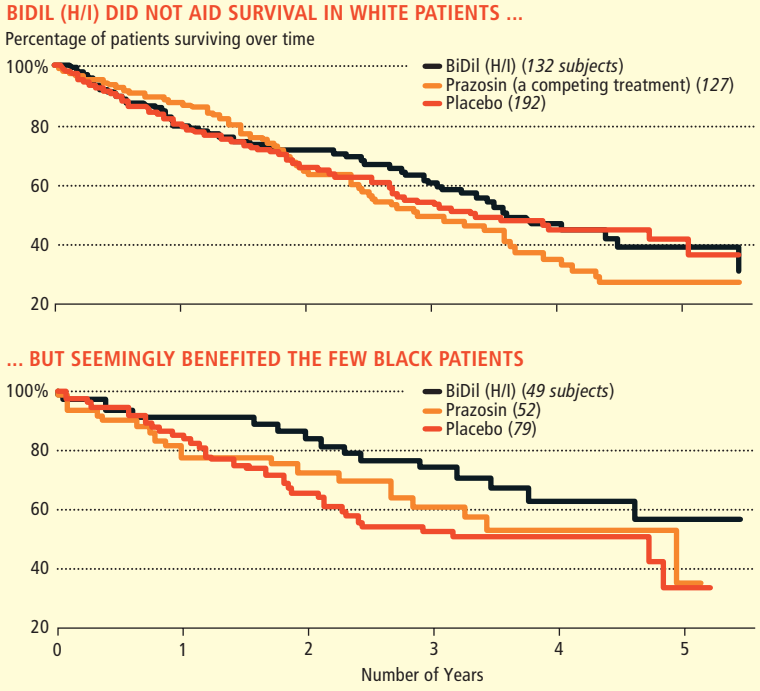
Segregated Medicine

Science and commerce have always proceeded together in advancing medicine, but in the case of BiDil the balance seems to have gotten out of whack. There can be no doubt that Cohn and the other medical professionals behind the drug's development sincerely want to improve the lives of the many people suffering from heart failure. In this respect, the approval of BiDil is certainly a good thing. But Cohn and NitroMed have also used race to obtain commercial advantage. The patented drug costs about six times as much as the readily available generic equivalents. The high cost has already made many insurers reluctant to cover BiDil and may place it beyond the reach of the millions of Americans without health insurance. Moreover, the unprecedented media attention to the race-specific character of the drug may lead many doctors and patients alike to think that non-African-Americans should not get the drug, when, in fact, it might help prolong their lives.

Perhaps most problematically, the patent award and FDA approval of BiDil have given the imprimatur of the federal government to using race as a genetic category. Since the inception of the Human Genome Project, scientists have worked hard to ensure that the biological knowledge emerging from advances in genetic research is not used inappropriately to make socially constructed racial categories appear biologically given or natural. As a 2001 editorial in the journal *Nature Genetics* put it, "scientists have long been saying that at the genetic level there is more variation between two individuals in the same population than between populations and that there is no biological basis for 'race.' " More recently, an editorial in *Nature Biotechnology* asserted that "race is simply a poor proxy for the environmental and genetic causes of disease or

LOOKING FOR A TREND

After the FDA's rejection of BiDil in 1997, the drug's developers examined the trial results by race. They spotted a small positive effect among black patients, but because only 49 blacks were taking the drug in the trial, the results may not be meaningful.



LUCY READING-IKKANDA (*timeline and graphs*); SOURCE FOR GRAPHS: "RACIAL DIFFERENCES IN RESPONSE TO THERAPY FOR HEART FAILURE: ANALYSIS OF THE VASODILATOR–HEART FAILURE TRIALS," BY PETER CARSON, SUSAN ZIESCHE, GARY JOHNSON AND JAY N. COHN, IN *JOURNAL OF CARDIAC FAILURE*, VOL. 5, NO. 3, SEPTEMBER 1999

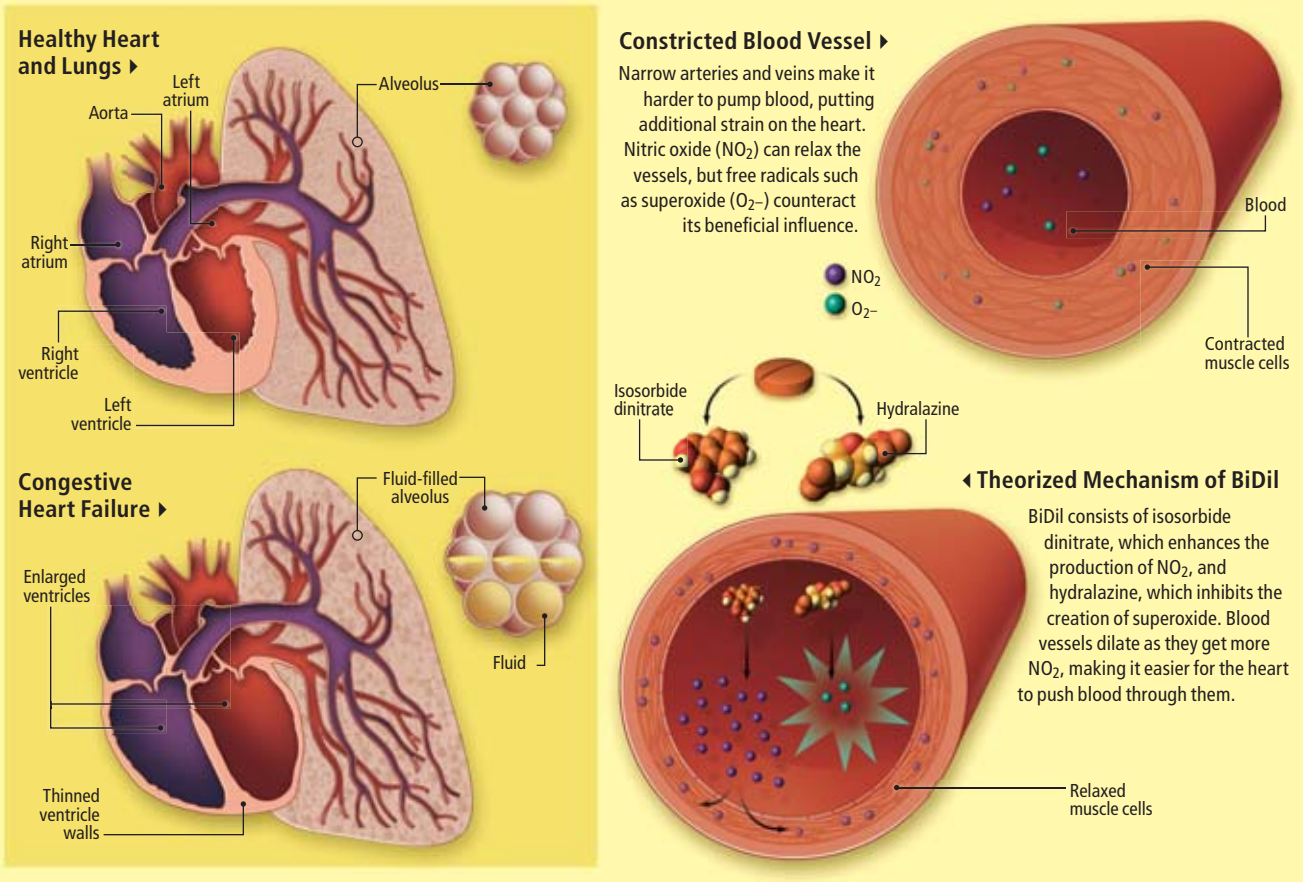
drug response.... Pooling people in race silos is akin to zoologists grouping raccoons, tigers and okapis on the basis that they are all stripey."

The FDA's approval of BiDil was based on accepting NitroMed's argument that the drug should be indicated only for African-Americans because the trial population was African-American. This labeling sends the scientifically unproved message that the subject population's race was somehow a relevant biological variable in assessing the safety and efficacy of BiDil. Most drugs on the market today were tested in overwhelmingly white populations, but we do not call these medicines "white," nor should we. The FDA's unstated assumption is that a drug that proves effective for white people is good enough for everyone; the same assumption should apply when the trial population happens to be black. Otherwise, the FDA is implying that African-Americans are somehow less fully representative of humanity than whites are.

In November 2004 *Nature Genetics* published an article by Sarah K. Tate and David B. Goldstein of University College London entitled "Will Tomorrow's Medicines Work for Everyone?" The paper noted that "29 medicines (or combinations of medicines) have been claimed, in peer-reviewed scientific or medical journals, to have differences in either safety or, more commonly, efficacy among racial or ethnic groups." Journalists immediately quoted the study as providing further evidence of biological differences among races; for example, an article in the *Los Angeles Times,* after discussing BiDil, referred to "a report in the journal *Nature Genetics* last month [that] listed 29 drugs that are *known* to have different efficacies in the two races." (The italics are mine.) Similarly, a story in the *Times of London* asserted that "only last week, *Nature Genetics* revealed research from University College London *showing* that 29 medicines have safety or efficacy profiles that vary between ethnic or racial groups." (Again, the italics are mine.) And a *New York Times* editorial entitled

HOW BIDIL TREATS HEART FAILURE

Unlike a healthy person's heart, a failing heart gets larger as it struggles to pump blood and causes fluid to accumulate in the lungs' alveoli. BiDil is thought to slow the progress of the disorder by dilating narrow blood vessels, which can ease the burden on the heart.



TAMI TOLPA

"Toward the First Racial Medicine" began with a discussion of BiDil and went on to note that "by one count, some 29 medicines show evidence of being safer or more effective in one racial group or another, suggesting that more targeted medicines may be coming."

One small problem: these newspaper stories totally misrepresented the *Nature Genetics* piece. Tate and Goldstein asserted that the racial differences in drug safety or efficacy have only been claimed, not proved, and in the next sentence they go on to say, "But these claims are universally controversial, and there is *no consensus* on how important race or ethnicity is in determining drug response." (My italics again.)

In only four of the 29 medicines identified, Tate and Goldstein found evidence that genetic variations between races could possibly be related to the different responses to the drugs. (All four are beta blockers used for treating high blood pressure and other cardiovascular ills; some research indicates that these drugs work better in individuals carrying a gene variant that is more common in people of European ancestry than in African-Americans.) For nine of the medicines, the authors found "a reasonable underlying physiological basis" to explain why blacks and whites may respond differently to the drugs; for example, some scientists have speculated that ACE inhibitors may be more effective in people of European descent than in African-Americans because of variations in enzyme activity. (Other researchers have contested this hypothesis.) For five of the drugs, Tate and Goldstein found no physiological reasons to explain the varying responses; for the remaining 11 they concluded that the reports of differing responses may not be valid.

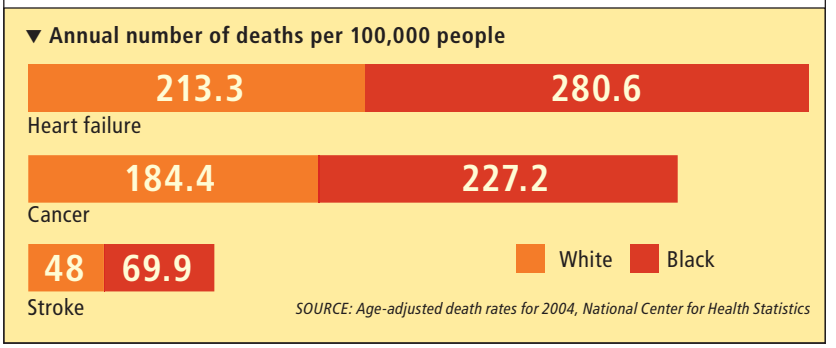
Racial Injustice

Nevertheless, the appeal of race-specific drugs is growing. In 2003 VaxGen, a California biopharmaceutical company, made an abortive attempt to use a retrospective analysis of racial subgroups to salvage a proposed AIDS vaccine called AIDSVAX. Although the clinical trial for AIDSVAX showed no decrease in HIV infection rates in the study population as a whole, VaxGen claimed a significant reduction in infection among the black and Asian participants. But only a few hundred blacks and Asians were involved in the study, meaning that a handful of infections could have skewed the results. The claim of race-specific response was undercut later that year when another trial in Thailand showed that AIDSVAX was ineffective there as well. In a similar case, AstraZeneca, the British pharmaceutical firm, argued that its lung cancer drug, Iressa, worked better in the Asians enrolled in a 2004 clinical trial, which showed that the medicine did not improve survival rates overall. (Unconvinced, the FDA changed the labeling for Iressa, disallowing its use in any new patients.) More recently, AstraZeneca has conducted trials of Crestor, the company's multibillion-dollar cholesterol-lowering drug, in African-Americans, South Asians and Hispanics. Consumer groups have claimed that Crestor is less safe than other cholesterol-lowering drugs, but AstraZeneca says the race-specific studies demonstrate the safety and efficacy of the medicine.

Researchers using race to develop drugs may be motivated by good intentions, but such efforts are also driven by the dictates of an increasingly competitive medical marketplace. The example of BiDil indicates that researchers and regulators alike have not fully appreciated that race is a powerful and volatile category. When used to bolster the commercial value of a drug, it can lead to haphazard regulation, substandard medical treatment and other unfortunate unintended consequences. The FDA should not grant race-specific approvals without clear and convincing evidence of a genetic or biological basis for any observed racial differences in safety or efficacy. Approving more drugs such as BiDil will not alleviate the very serious health disparities between races in the U.S. We need social and political will, not mislabeled medicines, to redress that injustice. ■

HEALTH IN BLACK AND WHITE

In the U.S., heart disease, cancer and stroke exact a greater toll on blacks than on whites. Although these diseases are the leading causes of death for both races, the age-adjusted death rates are much higher among African-Americans, meaning that they die at younger ages from the illnesses. Researchers have proposed several theories to explain the health disparity: whereas some experts put the blame on a lack of access to health care, others say the culprit is stress caused by low socioeconomic status.



MORE TO EXPLORE

The Meanings of "'Race" in the New Genomics: Implications for Health Disparities Research. Sandra Soo-Jin Lee et al. in *Yale Journal of Health Policy, Law, and Ethics,* Vol. 1, pages 33–75; 2001.

Combination of Isosorbide Dinitrate and Hydralazine in Blacks with Heart Failure. Ann L. Taylor et al. in *New England Journal of Medicine,* Vol. 351, pages 2049–2057; November 11, 2004.

How a Drug Becomes "Ethnic": Law, Commerce, and the Production of Racial Categories in Medicine. Jonathan Kahn in *Yale Journal of Health Policy, Law, and Ethics,* Vol. 4, pages 1–46; 2004.

From Disparity to Difference: How Race-Specific Medicines May Undermine Policies to Address Inequalities in Health Care. Jonathan Kahn in *Southern California Interdisciplinary Law Journal,* Vol. 15, pages 105–129; 2005.

Enhanced: Race and Reification in Science. Troy Duster in *Science,* Vol. 307, pages 1050–1051; February 18, 2005.

For other related articles by Jonathan Kahn, go to http://ssrn.com/author=180388

LUCY READING-IKKANDA

FIREFIGHTER contemplates a Washington State blaze.

Predicting Wildfires

Fires are burning more acres than ever. Where will the next blazes ignite? Can we prevent them? Should we?

By Patricia Andrews, Mark Finney and Mark Fischetti

KEY CONCEPTS

- Fuels are building up in forests because for decades agencies that manage these lands have attempted to put out almost all fires. Accumulation of deadwood and debris across large continuous tracts leads to extreme fires that are too expansive and hot to fight.
- Computer models are being used to predict how a current fire will burn and are getting better at forecasting which land areas are most susceptible to wildfire in the weeks, months or years ahead.
- The models are helping land managers better position fire crews and equipment so that they can jump on a blaze as soon as it starts, raising the chances of protecting people, property and natural resources.
- Other software is emerging that can gauge how future fires might be mitigated by thinning forests or allowing some fires to burn. These models can help land managers and agencies craft new policies that will lessen the chance for catastrophic fires and also restore fire as an integral part of natural ecosystems.

—The Editors

The number of catastrophic wildfires in the U.S. has been steadily rising. The nation has spent more than $1 billion annually to suppress such fires in eight of the past 10 years. In 2005 a record 8.7 million acres burned, only to be succeeded by 9.9 million acres in 2006. And this year is off to a furious start.

To a great extent, the increase in fires stems from a buildup of excess fuel, particularly deadwood and underbrush. Forests harbor more fuel than ever in large part because for decades, land management agencies, including the U.S. Forest Service, have followed a policy of trying to quickly put out every fire that starts. Fires, however, can clear out debris, preventing material from accumulating across wide areas and feeding extremely large, intense fires that become impossible to fight. Even in the absence of such a policy, firefighters find themselves compelled to combat many blazes because people continue to build homes further into wildlands, and those structures require protection. Exacerbating the problem, spring snowmelts have been occurring earlier, extending the number of weeks every year when forests are exposed and dangerously dry.

Clearly, the fuel supply needs to be reduced by allowing some naturally occurring fires to burn themselves out and by starting other burns. Fire is also important to the health of ecosystems; plant life has evolved with fire and depends on it. As wildfires skew to the extreme end of the size and intensity range, ecosystems that for millennia had depended on fire are being drastically altered, leaving them vulnerable to full-scale devastation from

AIR TANKER drops 2,500 gallons of retardant on a fire in Colorado.

diseases or insect infestation. Arizona's "sky islands"—small, high-altitude forests protruding from the desert—are already being lost to this very sequence. And wonderful old lodgepole forests in Colorado have been killed by bark beetle infestations that fire usually would have limited.

Unfortunately, it is difficult to know how much fuel must be removed to reduce the chance for extreme fires and how best to effect that removal. When should fires be set purposely to eliminate fuel? When should firefighters allow new fires to burn? To address such questions, policymakers, land managers and firefighting organizations need tools to test possible actions. In the past half a decade researchers have greatly improved computer models that capture how fires behave and provide firefighters with strategies for deciding how to handle them. Fire experts, climatologists and computer scientists are also devising large-scale models that can predict which tracts of land are ripe for fire in the next week, the next fire season and years ahead.

Fighting a Fire in Progress

Modeling how a fire will burn through a forest might seem to be an impossible task. A daunting number of variables must be considered: types of deadwood, the limb structures of trees, terrain, weather, moisture content of living leaves, moisture content of dead grasses and twigs (which can change hourly), and much more. Figuring out how to control a fire's spread involves even more variables, such as wind speed, ground slope, daily weather and the likely effects of firefighting tactics, among them dropping retardant from the air and bulldozing land to create barren firebreaks that flames have difficulty crossing.

Nevertheless, computer models capable of predicting the spread of a wildfire that has already started are becoming sophisticated. They are helping land managers and fire commanders make decisions that could save the lives of firefighters and area residents, as well as reduce the costs of battling the inevitable blazes. In 2006 some of the new modeling systems were used for the first time to influence where fire crews and equipment should be deployed. And this year they are coming into widespread use, already having helped fight early-season blazes in Florida, Georgia and California.

Technically speaking, a model refers to a set of algorithms that describe a single physical trait of a fire, such as the spread rate of flames. Programmers combine these models to create a fire-modeling system that land managers or fire danger analysts run on a computer to produce forecasts and maps. In daily parlance these systems end up being called models as well, and that is how we will use the term here.

In 1976 fire behavior analysts working on the ground alongside wildfires began consulting tables and graphs called nomograms to predict a fire's intensity, along with the rate and direction of its spread. These predictions were based on the types of fuel in the area (and their moisture content), wind speed and slope steepness (a fire advances up a slope much faster than on level ground). The analysts drew the results as vectors on a big topographic map for firefighters to see. Although expert judgment and manual methods of calculation will continue to be used in the field, computer software is surging.

The FARSITE fire area simulator developed by one of us (Finney) relies on similar inputs but also calculates where a fire might spread and how quickly. A fire behavior analyst enters a blaze's current position along with data on fuels, terrain and weather forecasts into a laptop, and FARSITE produces contoured graphics that depict the conflagration's growth for the next one to three days. This information helps fire managers decide which suppression tactics might be safest and most effective.

Large wildfires often burn for many more

[THE AUTHORS]

Patricia Andrews and Mark Finney have developed several of the leading computer models used throughout the U.S. to predict wildfires. Andrews is a research physical scientist at the Fire Sciences Laboratory in Missoula, Mont., run by the U.S. Forest Service. Finney is a research forester at the lab. Mark Fischetti is a staff editor at *Scientific American.*

KAREN WATTENMAKER (*preceding pages*); MIKE McMILLAN *Spotfire Images (top, this page)*; COURTESY OF U.S. FOREST SERVICE (*Andrews and Finney*)

days, however. Deciding where to position crews and equipment requires longer-term prediction. Another program, FSPro (for *f*ire *s*pread *pro*babilities), was developed by Finney for this task. He intended to run it on a trial basis for a few fires in 2006, but so many broke out during the season that fire managers ended up consulting FSPro on more than 70 blazes. The model calculates the probability of where a fire might spread by running thousands of FARSITE simulations, each with a different weather sequence that is based on historic climatology for the area. Projections can be made for as far out as 30 days. Knowing whether a fire is 20 or 80 percent likely to reach a community influences how fire crews work and whether residents should be evacuated. In general, FSPro predicted well where flames would spread, how quickly they would advance and how hot they would be; many managers found the model extremely helpful, although some said it tended to predict that fires would spread farther than they actually did.

Because FSPro runs thousands of scenarios, personal computers cannot handle the processing required. During all of 2006 and the spring of 2007, the Fire Sciences Laboratory in Missoula, Mont., overseen by the Research branch of the U.S. Forest Service, ran the model and sent contoured maps to fire crew commanders in the field. But in May, FSPro went online, allowing authorized analysts to enter data directly on the Web and to see the resulting maps there, too.

FSPro will improve as researchers finesse the basic physics-level models. For example, experts are only now creating reasonable models of crown fires—fires that sweep through the canopy of a forest instead of along the ground. Even

HOW WILL THE BLAZE SPREAD?

On July 23 and 24 of last year, lightning storms ignited multiple wildfires across the Shasta-Trinity National Forest in northern California. Fire crews sprang into action, but Joe Millar, the forest's fire management officer, quickly realized that four or five of the flare-ups could potentially grow large. How likely was that to happen, he wondered? Where should the crews concentrate their efforts?

Millar called Bernie Bahro, a regional liaison to several national agencies. Bahro, in turn, called Mark Finney at the Fire Sciences Laboratory in Missoula, Mont. To prepare for the worrisome blazes, Bahro wanted Finney to run FSPro (for *f*ire spread *pro*babilities)—a new computer model that predicts the probability of where and when a wildfire will spread. "We had 20 years of historical weather data, 10 years of wind data, and the data about how fuels were layered in the forest," Bahro says—the kinds of information FSPro needed. "We just had to get it all into Mark's machine."

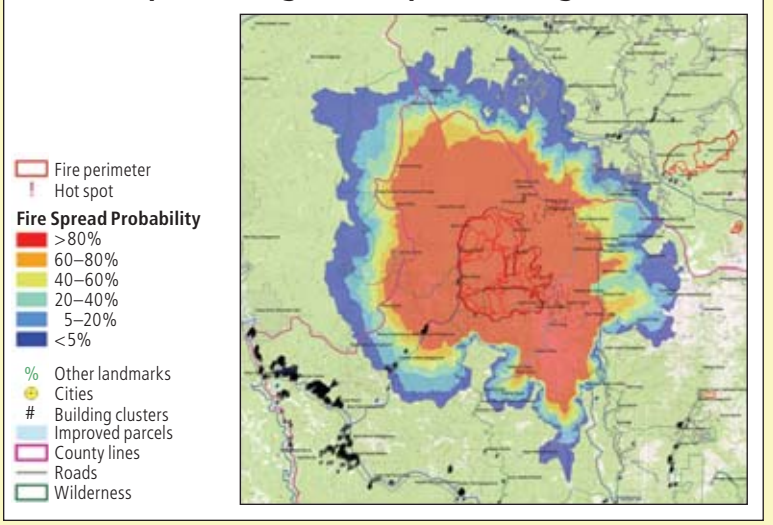
As Finney worked the software, fire crew commanders on the ground began calling in reports of how the fires were advancing. A day later Finney began e-mailing maps to Millar that showed where the fires were most likely to spread. By now six fires had grown large enough to warrant names and were burning just north and west of the forest headquarters in Redding, Calif., where Millar was located. "The simulations helped to orient me," Millar says. "They helped make clear that we needed to put a team on the Bake and Oven fires," which seemed to have the greatest potential to become larger, longer-term burns.

Bahro and Millar had also asked Finney and his colleague Dave Calkin to run another model, called Rapid Assessment of Values at Risk. This model pinpoints man-made structures as well as critical habitats and estimates their value, clues to which fires could impose the most dollar damage. "Early on we had teams trying to keep the Dog fire off private land," Millar says, "but as the Lakin fire got bigger we moved more resources there because we saw it was going to reach major power lines and a big utility pipeline."

After several weeks, firefighting teams had beaten back some of the blazes, but others stubbornly continued. Finney updated the models as crews submitted fresh information. The runs helped Bahro and Millar decide how to coordinate the teams and share big equipment. By August 29, FSPro showed that the combined conflagrations, now called the Big Bar Complex (*left*), could consume 286,000 acres, including scenic rivers, salmon habitats and a tribal area, but by moving crews, Millar and Bahro limited the toll to 104,000 acres. Millar emphasizes that the models did not dictate actions: "We still have to base decisions on the reality of what firefighters are seeing. But FSPro did show the tendency of where the fires wanted to go."

—Mark Fischetti

Potential Spread of Big Bar Complex Fire, August 29, 2006



FSPRO/RAVAR MAP, shown as fire managers saw it, helped to limit fire destruction.

PREPARED BY KEVIN HYDE (MET) FOR U.S. FOREST SERVICE, ROCKY MOUNTAIN RESEARCH STATION, FIRE SCIENCES AND FORESTRY SCIENCES LABS, MISSOULA, MONT.

less is understood about how a surface fire can suddenly transform into a crown fire. This switch can happen in minutes and is very dangerous because it can trap crews underneath a fire, making escape difficult. Better modeling of the transition point between the two fire types would help crews know when and where they can effectively operate.

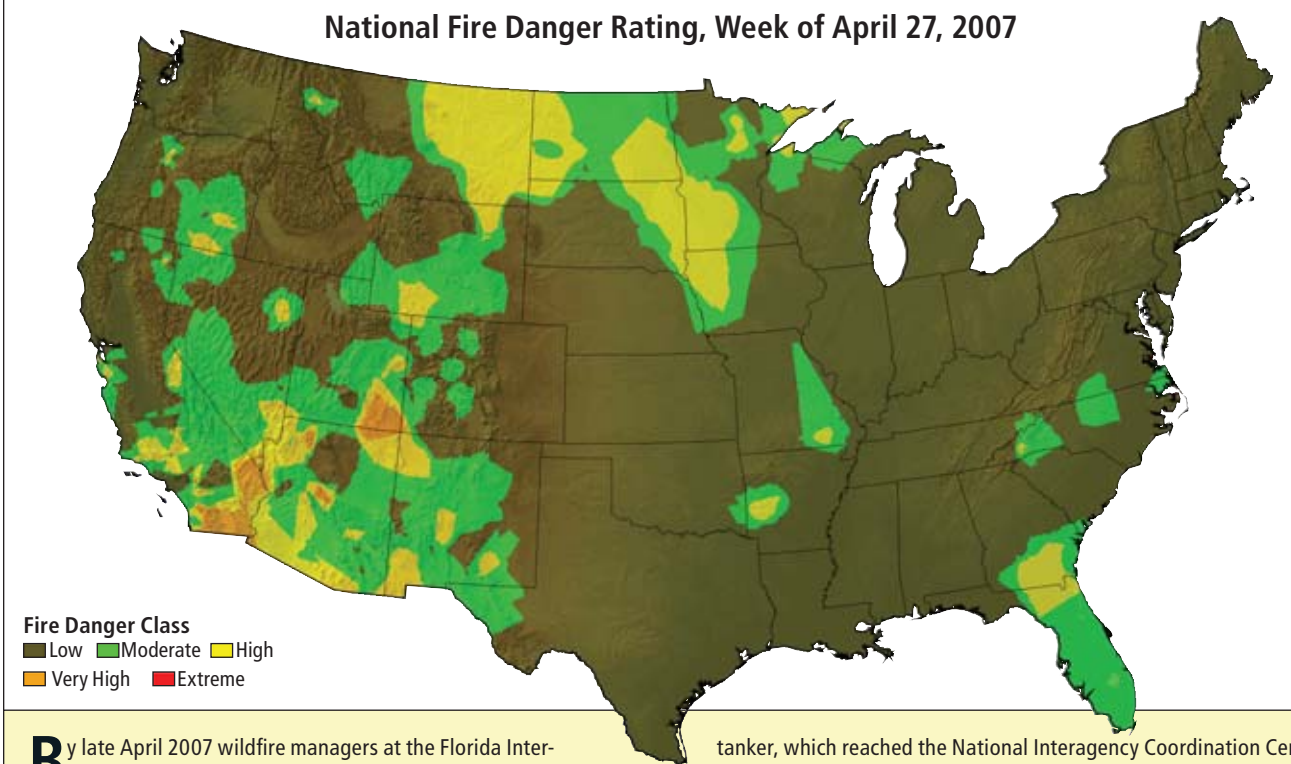
Forecasting Next Week, Next Month

Firefighters have the best chance of putting out a blaze if they can jump on it as soon as it ignites. Quick response is much more likely if fire managers have a good idea where the next fires will likely arise, allowing them to position crews before they do—and to warn the public to be extra cautious about accidentally starting a fire in those areas.

Models that predict fire potential for the upcoming few days or the week in a given forest or grassland look primarily at how damp the fuels are. Moisture levels for grasses and needle litter change daily with the weather, whereas the moisture content of logs and living leaves changes gradually over weeks and months.

U.S. scientists began predicting fire danger as early as 1916, based largely on anecdotal evidence and opinions of experienced fire behavior analysts. Mathematical models led to the National Fire Danger Rating System (NFDRS) in

WHERE WILL THE NEXT FIRE IGNITE?



By late April 2007 wildfire managers at the Florida Interagency Coordination Center had become concerned that wildfires would flare up across the northeastern corner of their state. An unusually prolonged drought had left leaves and grasses very dry. And the U.S. Forest Service had just issued a weekly fire danger map from the Wildland Fire Assessment System (WFAS) that indicated a high risk for fires in the region (*above*).

Several small fires were already burning, and the managers determined that if more ignited, firefighters would not have sufficient equipment to battle them. An additional air tanker would help them jump on new fires quickly, but there are only 18 available for nationwide use. None could be borrowed from the southwestern states, where the WFAS showed the risk for wildfires was also high.

On April 25 the Florida managers placed a request for another air tanker, which reached the National Interagency Coordination Center in Boise, Idaho. The Boise supervisors reviewed the WFAS maps, checked with local experts in California where fire danger was low, and identified an aircraft there. It took off on April 27 and arrived ready for duty in Florida the next day.

The move was well timed; in the following two weeks, 17 new fires ignited in Florida's national forests. Yet none of them became large because firefighters could attack them early, aided by air support, according to Matt Jolly of the Fire Sciences Laboratory in Missoula, Mont., who provided the details for this report. Wildfire managers across the country use models to continuously evaluate regional changes in fire danger and decide where to move crews and gear. Quite often, however, there is not enough of either to go around.

—***Mark Fischetti***

FIRE BEHAVIOR RESEARCH, MISSOULA, MONT.

1972, which has been gradually improved. Among other applications, forest managers and park rangers use these fire danger ratings to tell the public the risk for fire on a given day, information that is often imparted through the familiar Smokey Bear signs that list the danger from low to extreme.

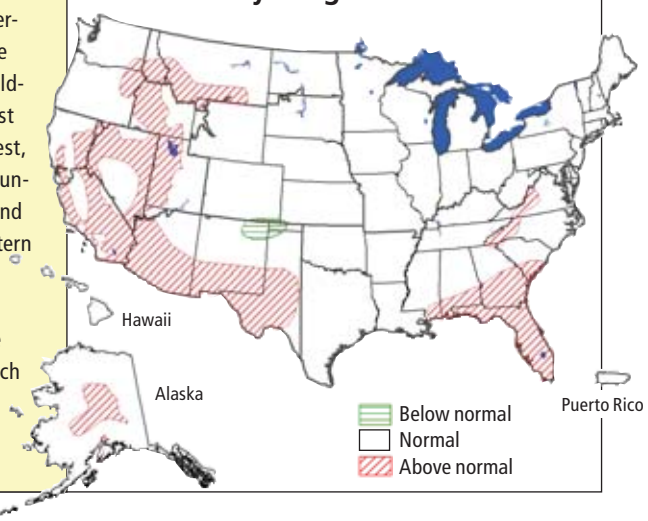
Today's fire danger ratings from the NFDRS are presented as maps in the Wildland Fire Assessment System (WFAS), developed at the Missoula lab. The WFAS automatically receives daily information from more than 1,800 fire weather stations across the U.S. that record meteorological data germane to fire risk, such as humidity and wind speed. The system calculates the danger indices and produces contoured maps in color for regions nationwide.

If the risk in a region is extremely high, land managers or local officials may take unusual measures to mitigate it, such as forbidding the public to enter a forest or banning stores from selling fireworks. Local field commanders use the WFAS maps to make decisions such as where to move their fire crews, and whether to keep them on overtime for a weekend so that they will be ready to respond immediately to new ignitions. When fire risk grew extreme in northern Florida this past April, national officials agreed to fly an air tanker there from a low-risk location in northern California; the tanker ended up providing crucial help when fires ignited only days later [*see box on opposite page*].

Staging crews and gear is expensive. What is more, although the public claims to support fire prevention, eager hunters, fishers and vacationers often become upset if they are forbidden to enter the woods. And local businesses can lose revenues. For these and other reasons, researchers are trying to improve the accuracy of the WFAS. One area of work involves the fire weather stations that provide data. Because these stations are very unevenly distributed across the country, the resulting maps may reflect actual conditions accurately in some areas but be far off the mark in others. This year the WFAS will therefore begin downloading current weather data from the National Oceanic and Atmospheric Administration's National Weather Service reporting stations (typically located at airports) and will also consult NOAA's own weather forecast models. With these inputs, the WFAS will be able to calculate a more reliable fire danger rating every five miles nationwide. The system also uses satellite data to track the moisture levels of live vegetation and will soon be updated to incorporate information from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) satellite.

THREAT FOR 2007

The Significant Fire Potential Outlook map issued by Predictive Services indicates that the greatest chance for wildfire from May to August 2007 is in the Southwest, parts of the Rocky Mountains, central Alaska and the extreme southeastern U.S. Every July the group issues another map for the rest of the year's fire season, which runs through October.



WILDFIRE'S TOLL

U.S. Acres Burned

2006 **9.9** million
2005 **8.7** million
2004 **8.0** million
2003 **4.0** million
2002 **7.2** million

Assessing the Next Season

Regardless of progress, fires will always happen. The practical question for an upcoming fire season is whether a given region will need more assets than normal to protect natural resources and the public. Will additional funds be needed for fire suppression? Should more crews be hired and trained?

Right now meteorologists and fire behavior analysts in the Predictive Services program, managed by the National Interagency Coordination Center (NICC) in Boise, Idaho, issue maps of weekly, monthly and seasonal outlooks of where the potential for fire is greatest. The maps are based on WFAS projections, but other factors that are hard to pin down must be woven in as well. Long periods of parched soil can result in dry trees, for example. In the western U.S., an arid spring with low snowpack can set the stage for an active summer fire season, whereas if rains come every 10 days far fewer fires than normal will erupt. Ultimately, accurate prediction of a future fire season depends on the ability to forecast the weather months ahead, which is not possible.

Experts at Predictive Services therefore focus on the potential impacts of various climate patterns. They meet with climatologists and other specialists at a workshop in January to devise regional assessments for the eastern, southern and

PREDICTIVE SERVICES, NATIONAL INTERAGENCY COORDINATION CENTER, BOISE, IDAHO

southwestern areas of the country. The group meets again in early April to assess the western region and Alaska. These assessments take models into consideration as well as anecdotal information about drought, seasonal weather patterns such as El Niño and La Niña (both of which alter the path of prevailing winds) and historic data that show how many large fires occurred during certain climatological conditions. The final result of the workshops is a significant fire potential forecast map that identifies areas where wildfires will likely require resources beyond those typically available. For 2007, much of the Southwest and the extreme Southeast were deemed to face high risk [*see box on page 51*].

Every year participants also debate how to incorporate new inputs. For example, at the 2007 meetings they discussed findings published in 2006 by Anthony Westerling, then at the Scripps Institution of Oceanography, and his colleagues. Westerling's group compiled data from 1,166 wildfires in the western U.S. that occurred between 1970 and 2003, along with the timing of snowmelts and spring and summer temperatures for those years. Participants of the workshop acknowledged the study's conclusions that an earlier spring snowmelt in mountainous regions is the leading factor in predicting where an above-average number of large wildfires will start.

BATTLING BLAZES

Firefighters who combat wildfires nationwide move around the U.S. as needed.

513 20-PERSON CREWS (10,260 firefighters)

446 SMOKE JUMPERS

87 HELICOPTERS

18 AIR TANKERS

Strategy for Years Ahead

Models that predict where fires are most likely during a current season are valuable on many practical levels. But if the country is to adopt policies that can reduce severe blazes, decrease the cost of firefighting and also restore the natural role of fire in ecosystems, then experts must predict the long-term effects of various land

WISER POLICIES COULD LESSEN CATASTROPHE

Despite ever improving firefighting techniques and technologies, record numbers of acres continue to burn in the U.S. The legacy of past policies is one cause, particularly the charge to put out as many fires as possible.

For decades, scientists and land managers have informed policymakers that extinguishing all fires has the paradoxical effect of making future fires larger and hotter. When fires are not permitted to burn, fuels accumulate across vast contiguous tracts: deadwood piles up, brush and new trees grow in thick, and tree canopies become dense. When a fire does ignite, there is so much fuel across such a wide area that no level of firefighting can contain it, causing severe consequences.

Changing such policies is a difficult proposition, however, because the basic solutions call for more fire, not less. Nevertheless, to avoid the most damaging fires, an enlightened approach should be considered by the many agencies that manage wildlands, including the U.S. Forest Service, National Park Service, U.S. Fish and Wildlife Service, Bureau of Land Management, Bureau of Indian Affairs and their counterparts at the state level. Although the Federal Wildland Fire Management Policy, set in 1995 and updated in 2001, recognizes that full suppression has undesirable consequences, the policy does not provide simple solutions.

Three primary changes would be instrumental. First, certain fires that start naturally—or portions of them—should be allowed to burn. Firefighters would protect important properties such as homes, power lines and watersheds, but in other areas flames would run their course.

Second, more prescribed burning should be pursued. Although this measure is now carried out to some degree, more fires must be set across larger areas, particularly in ecosystems dependent on fire and on lands close to developed areas where wildfires pose heightened risk.

FIRE CREW starts a prescribed burn in Los Padres National Forest.

Third, some brush, low-hanging tree limbs and small trees must be thinned, especially in places close to where people live and work. Ironically, one hurdle to accomplishing this is the objection from certain environmental groups suspicious that plans for thinning are veiled attempts to increase logging. Some forest types, once properly thinned, have been proved to survive wildfires that occur under extreme weather conditions.

The susceptibility of homes and private property to destruction must also be reduced. Certain municipalities in fire-prone areas of California, for example, now ban wood siding and require property owners to clear brush within 100 feet of their structures, to lessen the chance that buildings will ignite. Governments might also advise landowners that certain areas may be too remote to expect protection. As Tom Harbour, head of firefighting for the U.S. Forest Service, told *USA Today* in May, "We need to be telling people with even more clarity that just because you built something here, we're not going to die for it."

Modeling can help fire managers apply these new policies. The simulations can predict the probable impacts of letting certain parts of wildfires burn, as well as the effectiveness of techniques for managing those burns. The models can also help land managers decide where and when to set prescribed fires or how much accumulated fuel to clear. Over time, model makers would track how well the predicted and observed effects match and would adjust the models to improve them, in turn leading to more finely tuned policy changes. — ***Mark Finney***

MIKE McMILLAN *Spotfire Images*

management strategies. Such measures include not suppressing all fires, igniting controlled burns and manually thinning forests.

The Forest Vegetation Simulator is one software project that can demonstrate such long-term effects. It models tree growth, death and regeneration. A Fire and Fuels Extension to the simulator allows analysts to gauge the extent to which thinning trees or setting a prescribed burn would alter the severity of a future fire. The Stand Visualization System can then create images of the results. For example, the software suite can compare how a wildfire in 2065 might affect a stand of trees if no management had taken place there since 2007 or if a prescribed fire had been set. The programs continue to be improved.

Another way to assess the long term is to consider the likely buildup of fuel. The FlamMap model calculates how a fire would behave across a landscape given the present fuel structure, under different weather conditions. Fire managers have applied FlamMap to the Sierra Nevada Mountains in California to help them prioritize which areas might benefit from thinning and prescribed burning. Analysts can also use the BehavePlus model (developed by Andrews and others) to consider whether a prescribed fire might be a viable option in an area analyzed by FlamMap. BehavePlus determines the conditions under which such a fire would not escape the planned burn area, given differing winds and fuel moisture: if fuels are wet, a higher wind speed would be acceptable than that for dry fuels. For contingency planning, the system can indicate how far from the burn wind could carry hot embers and the chances of them starting a spot fire outside the planned area.

Land managers decide to light prescribed fires more often than most people think. In the U.S. in 2006, more than 2.7 million acres were burned by more than 24,000 such fires, according to the NICC. Managers are eager for better models that can help assure that a planned fire is safe and effective. In response, systems are being enhanced so they can better predict such concerns as fire intensity (heat level) and smoke production (too much smoke can make highways impassable or air quality dangerous for a nearby community).

Better Basics Needed

Scientists, engineers, computer programmers and forestry experts continue to enhance prediction models; we have described only some examples here. Certain models complement one another; some compete. In the end, they will have to be combined or connected to give fire managers the most helpful, integrated views.

Part of that work will be to further improve the basic physical-level models that underlie all these systems, such as those that calculate flame length or rate of flame spread. A wildfire is a moving combustion reaction with limitless access to oxygen and fuel. The fuel varies in an infinite combination of particle sizes, compactness, dampness and spatial distribution. Weather impacts change continuously. As a result, even the best attempts to quantify variables require simplifying assumptions. Researchers are thus looking to other disciplines to attack the problem. One promising avenue is computational fluid dynamics, an expanding discipline. It is well suited to fire modeling because it can simulate combustion kinetics, chemistry and heat transfer. The technique requires vast computing, however.

Improving models and establishing their scientific credibility also rest on comparing their outputs against observations of actual fires. The difficulty posed to firefighters and researchers attempting to obtain precise field measurements makes this a challenge in itself. Models will also improve as we get a better handle on the most fickle aspects of a wildfire, such as transitions from surface fires to crown fires, as well as spot fires that are ignited ahead of a flame front by windblown embers.

Nevertheless, after decades of modest progress, advancement in fire modeling has surged in the past five years. In perhaps just a few years more, the programs could be integrated into a cohesive set that would help fire analysts and land managers predict the likelihood of fire and advise policymakers on how best to reduce risk while also allowing nature to take its course. ■

SCI AM

To see how experts created the Significant Fire Potential map for May-August 2007, log on to **www.SciAm.com/ontheweb**

SURFACE FIRES (*bottom*) can quickly transition to crown fires (*top*), but better models are needed to predict such changes.

MIKE McMILLAN *Spotfire Images (top);* MARK EDWARDS *Peter Arnold, Inc. (bottom)*

MORE TO EXPLORE

Current wildland fire information from the National Interagency Fire Center: www.nifc.gov/information.html

Fire behavior and fire danger software: www.firemodels.org

U.S. Federal Fire Policy: www.nifc.gov/fire_policy

Ways to protect homes and communities against wildfires: www.firewise.org

Once scorned as nervous tics, certain tiny, unconscious flicks of the eyes now turn out to underpin much of our ability to see. These movements may even reveal subliminal thoughts

By Susana Martinez-Conde and Stephen L. Macknik

Windows on the

KEY CONCEPTS

- When the eyes fix on something, they still jump imperceptibly in ways that turn out to be essential for seeing.
- For decades, scientists have debated the purpose, if any, of these so-called fixational eye movements, the largest of which are called microsaccades. Now the authors have demonstrated that microsaccades engender visibility when a person's gaze is fixed and that bigger and faster microsaccades work best.
- Microsaccades may also shed light on subliminal thoughts. Recent research suggests that the direction of microsaccades is biased toward objects to which people are unconsciously attracted, no matter where they are actually looking.

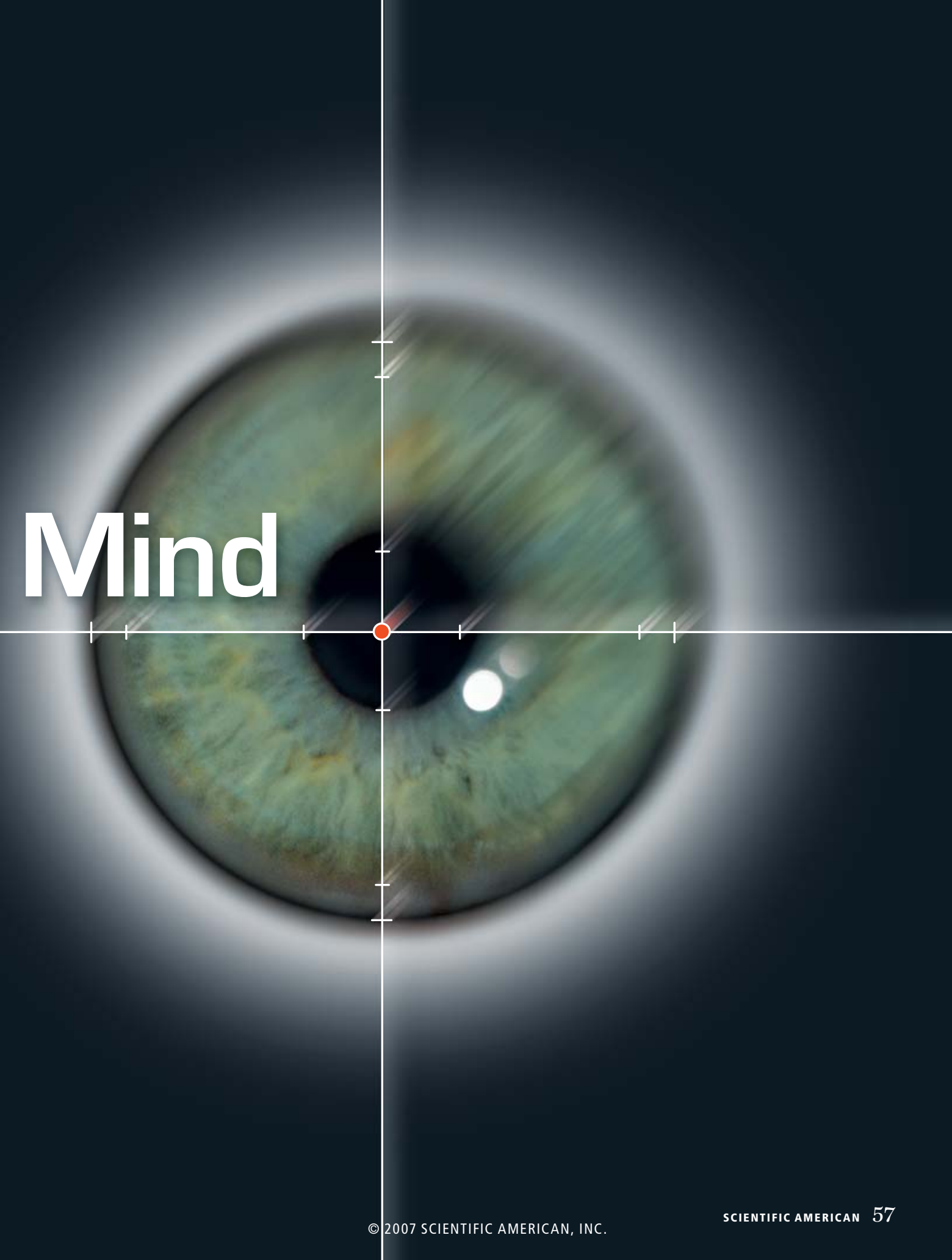
—*The Editors*

As you read this, your eyes are rapidly flicking from left to right in small hops, bringing each word sequentially into focus. When you stare at a person's face, your eyes will similarly dart here and there, resting momentarily on one eye, the other eye, nose, mouth and other features. With a little introspection, you can detect this frequent flexing of your eye muscles as you scan a page, face or scene.

But these large voluntary eye movements, called saccades, turn out to be just a small part of the daily workout your eye muscles get. Your eyes *never* stop moving, even when they are apparently settled, say, on a person's nose or a sailboat bobbing on the horizon. When the eyes fixate on something, as they do for 80 percent of your waking hours, they still jump and jiggle imperceptibly in ways that turn out to be essential for seeing. If you could somehow halt these miniature motions while fixing your gaze, a static scene would simply fade from view.

And yet only recently have researchers come to appreciate the profound importance of such "fixational" eye movements. For five decades, a debate has raged about whether the largest of these involuntary movements, the so-called microsaccades, serve any purpose at all. Some sci-

JENS NIETH *zefa/Corbis (photograph)*; JEN CHRISTIANSEN (*photoillustration*)



Tiny subconscious eye movements are helping neuroscientists crack the brain's code for conscious visual perceptions.

entists have opined that microsaccades might even impair eyesight by blurring it. But recent work in the laboratory of one of us (Martinez-Conde) at the Barrow Neurological Institute in Phoenix has made the strongest case yet that these minuscule ocular meanderings separate vision from blindness when a person looks out at a stationary world.

Meanwhile microsaccades are also helping neuroscientists crack the brain's code for creating conscious perceptions of the visual world. In the past few years, we and others have detected telltale patterns of neural activity that correlate with these little movements, which we now believe drive most of what people perceive. What is more, microsaccades may form a window into your mind. Instead of being random, these little ocular shifts may point to where your mind is secretly focusing—even if your gaze is directed elsewhere—revealing hidden thoughts and desires.

Fatigued by Sameness

That the eyes move constantly has been known for centuries. For example, in 1860 German doctor and physicist Hermann von Helmholtz pointed out that keeping one's eyes motionless was a difficult proposition and suggested that "wandering of the gaze" prevented the retina, several layers of cells at the back of the eye, from becoming tired.

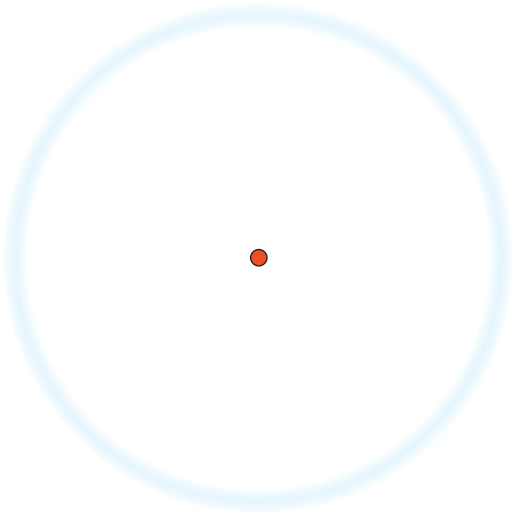
Indeed, animal nervous systems have evolved to detect changes in the environment, because spotting differences promotes survival. Motion in the visual field may indicate that a predator is approaching or that prey is escaping. Such changes prompt visual neurons to respond with electrochemical impulses. Unchanging objects do not generally pose a threat, so animal brains—and visual systems—did not evolve to notice them. Frogs are an extreme case. A fly sitting still on the wall is invisible to a frog, as are all static objects. But once the fly is aloft, the frog will immediately detect it and capture it with its tongue.

Frogs cannot see unmoving objects because, as Helmholtz hypothesized, an unchanging stimulus leads to neural adaptation, in which visual neurons adjust their output such that they gradually stop responding. Neural adaptation

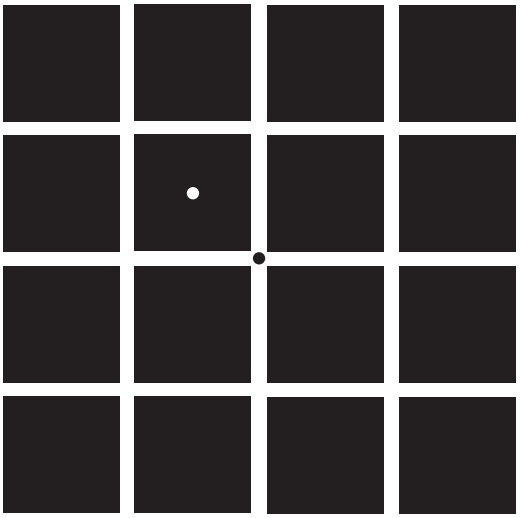
SOURCES: IGNAZ PAUL VITAL TROXLER *(left)*; "A SIMPLE AFTER IMAGE METHOD DEMONSTRATING THE INVOLUNTARY MULTIDIRECTIONAL EYE MOVEMENTS DURING FIXATION," BY F. J. VERHEIJEN, IN *JOURNAL OF MODERN OPTICS*, VOL. 8, NO. 4, PAGES 309–312; OCTOBER 1961; © TAYLOR AND FRANCIS LTD. *(right)*

MINIATURE EYE MOVEMENTS REVEALED

With these three illusions, you can observe various visual effects of your fixational eye movements, which are typically beneath your awareness.



TROXLER TEST: In 1804 Swiss philosopher Ignaz Paul Vital Troxler discovered that deliberately focusing on something causes surrounding stationary images to fade away. To elicit this experience, stare at the red spot while paying attention to the pale blue circle. The circle soon vanishes, and the red spot appears set against a white background. Move your eyes, and it pops back into view.



SEEING THE EYES MOVE: Here is a way to "see" your fixational eye movements. Look at the central black dot for about a minute, then look at the white dot in the adjacent dark square. Notice that the dark afterimage of the white cross-hatching is in constant motion. That is a result of your fixational eye movements.

saves energy but also limits sensory perception. Human neurons also adapt to sameness. But the human visual system does much better than a frog's at detecting unmoving objects, because human eyes create their own motion. Fixational eye movements shift the entire visual scene across the retina, prodding visual neurons into action and counteracting neural adaptation. They thus prevent stationary objects from fading away.

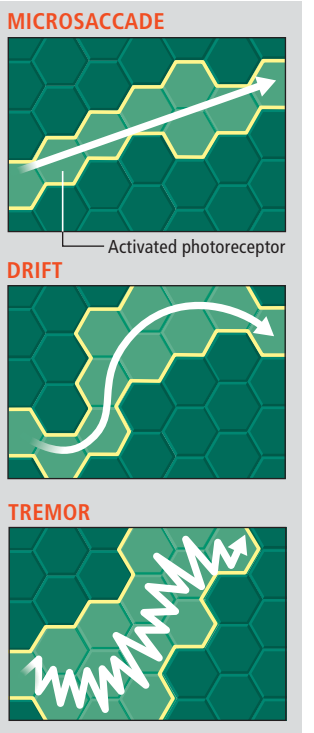
In 1804 Swiss philosopher Ignaz Paul Vital Troxler reported the first fading phenomenon in humans related to a decrease in fixational eye movements. Troxler noted that deliberately focusing on something causes stationary images in the surrounding region to gradually fade away [*see left illustration in box on opposite page*]. This fading happens to you every day, because deliberately focusing on something can briefly slow or reduce fixational eye movements, which are also less effective outside your area of focus. Thus, even a small reduction in the rate and size of your eye movements greatly impairs your vision. You do not notice the impairment, because you are not paying attention to invisible portions of your view, focusing on what is directly in front of you instead.

Totally ceasing all eye movements, however, can only be done in a laboratory. In the early 1950s some research teams achieved this stilling effect by mounting a tiny slide projector onto a contact lens and affixing the lens to a person's eye with a suction device. In this setup, a subject views the projected image through this lens, which moves with the eye. Using such a retinal stabilization technique, the image remains still with respect to the eye, causing the visual neurons to adapt and the image to fade away. Nowadays researchers create this same result by measuring the eye's movements with a camera pointed at it. They transmit the eye-position data to a projection system that moves the image with the eye.

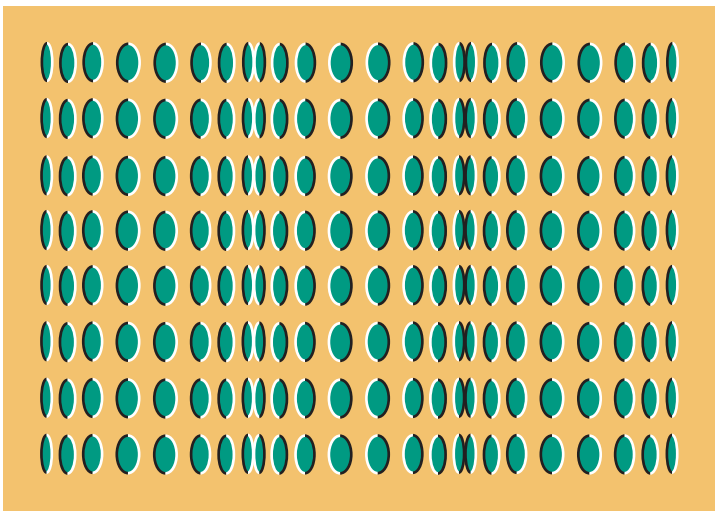
In the late 1950s researchers were able to isolate a role for microsaccades: after suppressing all eye movements in the lab, including the larger voluntary saccades, they superimposed microsaccadelike motions and found that doing so restored perception. Other research teams, however, found otherwise: adding back

MOVING TARGETS

Fixational eye movements, including microsaccades (straight lines), drifts (wavy lines) and tremor (zigzags superimposed on drifts), transport the visual image over a mosaic of photoreceptors on the retina.



JEN CHRISTIANSEN (*diagrams at right*); SOURCE: AKIYOSHI KITAOKA, © 2004 (*below*)

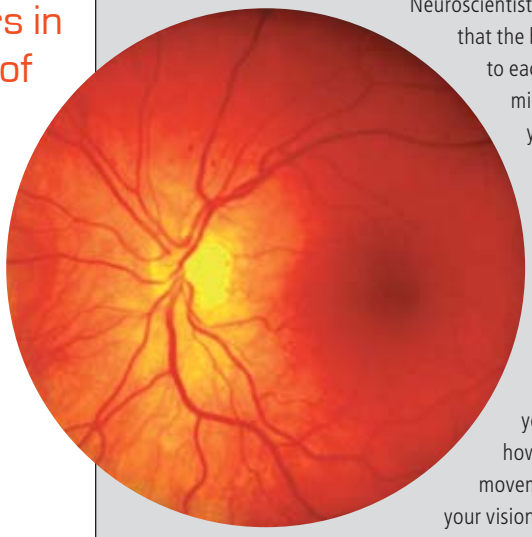


ILLUSORY MOTION: Let your eyes wander around the pattern above, and the three "rollers" will appear to spin. But if you hold your gaze steady on one of the green spots in the center of the image, the illusory motion will slow down or even stop. Because holding the eyes still stops the illusory motion, the authors speculate that the fixational eye movements may be required to see it, although they do not yet know exactly how.

Microsaccades elicit neuronal rejoinders in every part of the visual system we have examined.

[DO-IT-YOURSELF]

VANISHING VESSELS



Neuroscientists David Coppola and Dale Purves of Duke University showed that the blood vessels in the retina, which are stationary with respect to each eye, can fade from a person's view in a mere 80 milliseconds (thousandths of a second). You can see this for yourself. Close your eyes while lightly holding a small flashlight (not too bright!) up to the side of one of your eyes. If you move the flashlight around rapidly, you might catch a glimpse of your retinal blood vessels in your peripheral vision. But notice how quickly they fade from view.

Neural adaptation takes place in all of the senses, including touch. For instance, you may feel your shoes when you first put them on in the morning, but the feeling goes away after a while. You probably do not want to be aware of your shoes 16 hours a day, after all. If you wiggle your toes, however, you can feel your shoes again. Similarly, fixational eye movements constantly "wiggle" the images on the retina so that your vision never goes away. —*S.M.-C. and S.L.M.*

microsaccades after freezing eye movements had no effect at all in these experiments. The truth was hard to discern because none of the techniques for stabilizing the retina was perfect; for instance, a contact lens attached to the eye can slip, leaving some residual eye movements. In the end, no one could tell whether an experimental result was caused by those residual movements or the superimposed microsaccades.

Nervous Tics?

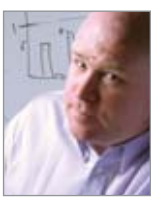
Around the same time, investigators identified two other flavors of fixational eye movements: drifts and tremor. Drifts are slow, meandering motions that occur between the fast, linear microsaccades. Tremor is a tiny, rapid oscillation superimposed on drifts. Microsaccades are the largest of the fixational eye movements, carrying an image across dozens to several hundred of the eye's photoreceptor (light-detecting) cells, including cones for detail and color vision and rods for low-light and peripheral vision. Tremor is the smallest of the fixational eye movements, its motion no bigger than the size of one of these cells. We do not yet understand the relative roles of these various fixational eye movements in vision, however.

In fact, for decades, many vision scientists doubted whether any of these fixational eye movements—especially microsaccades, which were the most studied—had a role in maintaining vision. Critics noted that some individuals could suppress microsaccades for a couple of seconds without their central vision fading away. (You can see this in the Troxler test; as you briefly suppress your microsaccades, the ring fades, but you can still see the red dot in the center of your view.) And people naturally hold microsaccades at bay momentarily when they perform precision tasks such as shooting a rifle or threading a needle. In 1980 University of Maryland psychologists Eileen Kowler and Robert M. Steinman concluded that microsaccades were useless, supposing that they might be "merely a kind of nervous tic."

There the field stood until the late 1990s, when researchers began to investigate which neuronal responses, if any, fixational eye movements might be generating in the eye and brain. Starting in 1997, along with Nobel laureate David Hubel of Harvard Medical School, we trained monkeys to fixate on a small spot presented on a computer monitor, which also displayed a stationary bar of light elsewhere on the screen. As the monkeys stared, we recorded their eye movements and the electrical activity from neurons in the lateral geniculate nucleus (LGN) in their midbrain and in the primary visual cortex at the back of their brain [*see box on opposite page*]. In each experiment the bar was placed in a location that would elicit an optimal electrical response—in the form of impulses called spikes—from the recorded neurons.

The results of these experiments, published in 2000 and 2002, showed that microsaccades increased the rate of neural impulses generated by both LGN and visual cortex neurons by ush-

[THE AUTHORS]



Susana Martinez-Conde is director of the Laboratory of Visual Neuroscience at the Barrow Neurological Institute in Phoenix. She holds a Ph.D. in medicine and surgery from the University of Santiago de Compostela in Spain. **Stephen L. Macknik** is director of the Laboratory of Behavioral Neurophysiology at the Barrow Neurological Institute and earned a Ph.D. in neurobiology from Harvard University.

STEVE ALLEN *Brand X/Corbis (top);* JEFF NOBLE *(Martinez-Conde and Macknik)*

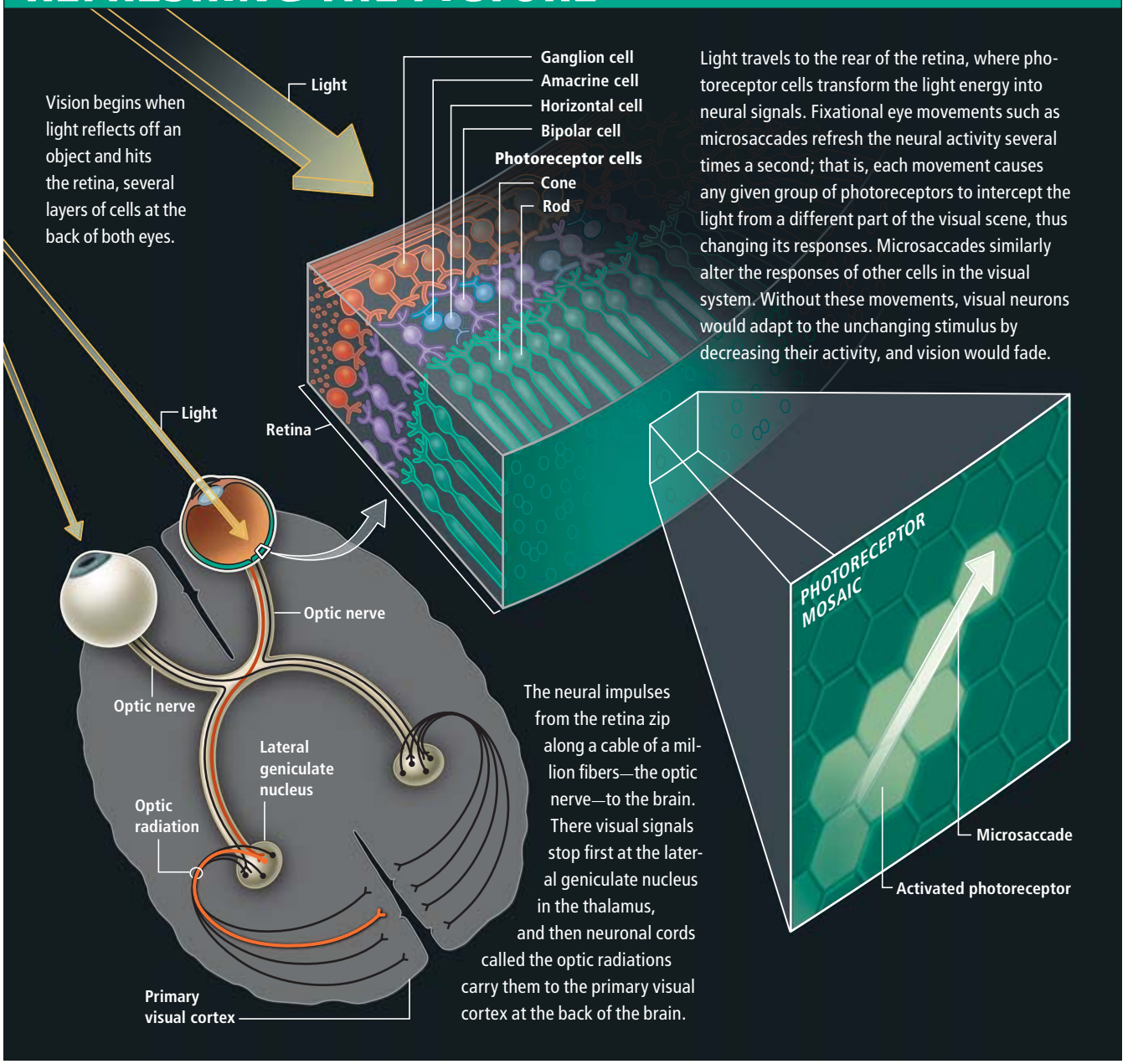
ering stationary stimuli, such as the bar of light, in and out of a neuron's receptive field, the region of visual space that activates it. This finding bolstered the case that microsaccades have an important role in preventing visual fading and maintaining a visible image. And assuming such a role for microsaccades, our neuronal studies of microsaccades also began to crack the visual system's code for visibility. In our monkey studies we found that microsaccades were more closely associated with rapid bursts of spikes than single spikes from brain neurons, suggesting that bursts of spikes are a signal in the brain that something is visible.

Cracking the Case

Other researchers also found that microsaccades elicit neuronal rejoinders in every part of the visual system that they examined. Nevertheless, the field was still haunted by the conflicting results in the retinal stabilization experiments, casting lingering doubt over the importance of microsaccades in vision. So a few years ago, at the Barrow Neurological Institute, we

[THE BASICS]

REFRESHING THE PICTURE



JEN CHRISTIANSEN

You may avert your eyes from that last piece of cake or an attractive man or woman near you, but the rate and direction of your microsaccades betray your true focus.

set out to directly measure the relation between microsaccades and visibility using a completely different technique. In our experiments, we asked volunteers to perform a version of Troxler's fading task. Our subjects were to fixate on a small spot while pressing or releasing a button to indicate whether they could see a static peripheral target. The target would vanish and then reappear as each subject naturally fixated more—and then less—at specific times during the course of the experiment. During the task, we measured each person's fixational eye movements with a high-precision video system.

As we had predicted, the subjects' microsaccades became sparser, smaller and slower just before the target vanished, indicating that a lack of microsaccades—or unusually small and slow microsaccades—leads to adaptation and fading. Also consistent with our hypothesis, microsaccades became more numerous, larger and faster right before the peripheral target reappeared. These results, published in 2006, demonstrated for the first time that microsaccades engender visibility when subjects try to fix their gaze on an image and that bigger and faster microsaccades work best for this purpose. And because the eyes are fixating—resting between the larger, voluntary saccades—the vast majority of the time, microsaccades are critical for most visual perception.

Such work is not just of theoretical import but might also have therapeutic implications. That is, a better understanding of the importance of fixational eye movements in vision may provide insights into diseases and conditions that impair these movements. For instance, a lack of fixational eye movements can result from paralysis of the oculomotor nerves, which control most of the eye movements. Abnormal fixational eye movements are also common in amblyopia, or "lazy eye," a loss of detail vision without any detectable pathology and the leading cause of vision loss in one eye among 20- to 70-year-olds. In severe amblyopia, excessive drift and too few microsaccades can cause objects and even large portions of the visual scene to fade away during fixation.

In normal vision the oculomotor system must achieve a delicate balance between too few fixational eye movements and too many, which lead to blurred and unstable vision during periods of fixation. Understanding how that eye-motion system achieves such a balance might one day enable doctors to recalibrate the system when something goes awry. A large number of disorders impact fixational eye movements, making this a fertile research field that so far remains largely unexplored.

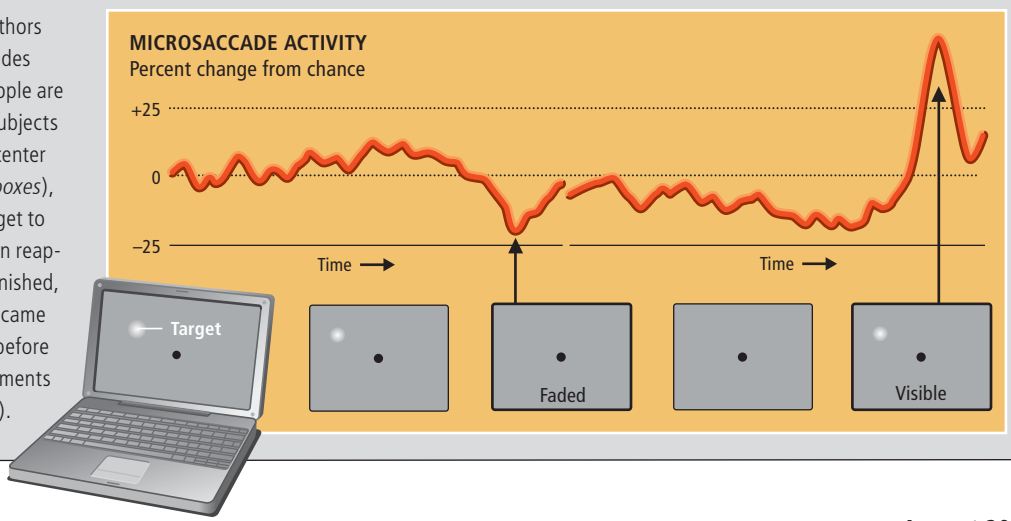
Reading the Mind

Microsaccades may have significance beyond vision. These little eye movements may also help expose a person's subliminal thoughts. Even when your gaze is fixed, your attention can unconsciously shift about a visual scene to objects that attract your interest, psychologists have found. Recent research suggests that microsaccades can reveal such objects of attraction because the direction of microsaccades, instead of being totally random, may point right to them—even if you are looking elsewhere.

Vision scientists Ziad M. Hafed and James J. Clark of McGill University asked volunteers

SEEING WITH MICROSACCADES

In a recent experiment, the authors demonstrated that microsaccades bring about visibility when people are fixing their gaze. They asked subjects to stare at a small spot in the center of a computer screen (*row of boxes*), causing a static peripheral target to vanish from their view and then reappear. Just before the target vanished, the viewers' microsaccades became sparser and slower, and right before it reappeared, these eye movements became more frequent (*graph*).



JEN CHRISTIANSEN

ATTENTION MONITOR: Scientists can track microsaccades to determine if something is secretly attracting a person's attention—such as a slice of chocolate cake—even when that person is looking elsewhere. But don't worry. Ordinary people cannot easily use these eye movements to read your mind.

to direct their eyes to a central spot on a computer monitor while paying attention to a peripheral spot that changed color at the end of each trial. The volunteers were supposed to indicate this color change. In 2002 Hafed and Clark reported that the direction of the subjects' microsaccades was biased toward their true point of focus, even though they were looking elsewhere. This finding indicated not only that microsaccades may point to people's covert thoughts but also, the authors noted, that covert shifts of attention actually control the direction of microsaccades.

In another experiment, computational neuroscientist Ralf Engbert and cognitive psychologist Reinhold Kliegl of the University of Potsdam in Germany found that the *frequency* of microsaccades also conveys the presence of something that secretly attracts a person's attention. The abrupt appearance of a visual cue in the periphery of a person's field of view, they stated in 2003, causes first a brief drop in the rate of microsaccades, followed by a rapid rebound in which microsaccade frequency exceeds normal. Furthermore, the microsaccades they detected were biased in the direction of the cue. The study suggests that microsaccade frequency and direction can signal sudden changes in the environment that attract a person's attention when he or she does not look directly at them.

Thus, no matter how hard you might avert your eyes from the last piece of cake on the table or the attractive male or female standing across the room, the rate and direction of your microsaccades betray your attentional spotlight. This betrayal is not a practical concern, however. In the laboratory, scientists can detect and measure these minuscule eye movements to reveal the hidden brain mechanisms of attention, but people around you cannot easily use them to read your mind—yet. ■

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MORE TO EXPLORE

Microsaccades as an Overt Measure of Covert Attention Shifts. Z. M. Hafed and J. J. Clark in *Vision Research,* Vol. 42, pages 2533–2545; 2002.

Microsaccades Uncover the Orientation of Covert Attention. R. Engbert and R. Kliegl in *Vision Research,* Vol. 43, pages 1035–1045; 2003.

The Role of Fixational Eye Movements in Visual Perception. S. Martinez-Conde, S. L. Macknik and D. H. Hubel in *Nature Reviews Neuroscience,* Vol. 5, pages 229–240; 2004.

Fixational Eye Movements in Normal and Pathological Vision. S. Martinez-Conde in *Progress in Brain Research,* Vol. 154, pages 151–176; 2006.

Microsaccades Counteract Visual Fading during Fixation. S. Martinez-Conde, S. L. Macknik, X. G. Troncoso and T. A. Dyar in *Neuron,* Vol. 49, pages 297–305; 2006.

Akiyoshi Kitaoka's illusion pages: www.ritsumei.ac.jp/~akitaoka/index-e.html

Martinez-Conde Laboratory: www.neuralcorrelate.com/smc_lab

BRIAN MARANAN PINEDA

The Physical Science behind CLIMATE CHANGE

By William Collins, Robert Colman, James Haywood, Martin R. Manning and Philip Mote

Why are climatologists so highly confident that human activities are dangerously warming the earth?

Here some of the participants in the most recent and comprehensive international review of the scientific evidence summarize the arguments and discuss what uncertainties remain

For a scientist studying climate change, "eureka" moments are unusually rare. Instead progress is generally made by a painstaking piecing together of evidence from every new temperature measurement, satellite sounding or climate-model experiment. Data get checked and rechecked, ideas tested over and over again. Do the observations fit the predicted changes? Could there be some alternative explanation? Good climate scientists, like all good scientists, want to ensure that the highest standards of proof apply to everything they discover.

And the evidence of change *has* mounted as climate records have grown longer, as our understanding of the climate system has improved and as climate models have become ever more reliable. Over the past 20 years, evidence that humans are affecting the climate has accumulated inexorably, and with it has come ever greater certainty across the scientific community in the reality of recent climate change and the potential for much greater change in the future. This increased certainty is starkly reflected in the latest report of the Intergovernmental Panel on Climate Change (IPCC), the fourth in a series of assessments of the state of knowledge on the topic, written and reviewed by hundreds of scientists worldwide.

The panel released a condensed version of the first part of the report, on the physical science basis of climate change, in February. Called the "Summary for Policymakers," it delivered to policymakers and ordinary people alike an unambiguous message: scientists are more confident than ever that humans have interfered with the climate and that further human-induced climate change is on the way. Although the report finds that some of these further changes are now inevitable, its analysis also confirms that the future, particularly in the longer term, remains largely in our hands—the magnitude of expected change depends on what humans choose to do about greenhouse gas emissions.

The physical science assessment focuses on four topics: drivers of climate change, changes observed in the climate system, understanding cause-and-effect relationships, and projection of future changes. Important advances in research into all these areas have occurred since the IPCC assessment in 2001. In the pages that follow, we lay out the key findings that document the extent of change and that point to the unavoidable conclusion that human activity is driving it.

Drivers of Climate Change

Atmospheric concentrations of many gases—primarily carbon dioxide, methane, nitrous oxide and halocarbons (gases once used widely as refrigerants and spray propellants)—have increased because of human activities. Such gases trap thermal energy (heat) within the atmosphere by means of the well-known greenhouse effect, leading to global warming. The atmospheric concentrations of carbon dioxide, methane and nitrous oxide remained roughly stable for nearly 10,000 years, before the abrupt and rapidly accelerating increases of the past 200 years [*see right illustrations in box on page 67*]. Growth rates for concentrations of carbon dioxide have been faster in the past 10 years than over any 10-year period since continuous atmospheric monitoring began in the 1950s, with concentrations now roughly 35 percent above preindustrial levels (which can be determined from air bubbles trapped in ice cores). Methane levels are roughly two and a half times preindustrial levels, and nitrous oxide levels are around 20 percent higher.

How can we be sure that humans are responsible for these increases? Some greenhouse gases (most of the halocarbons, for example) have no natural source. For other gases, two important observations demonstrate human influence. First, the geographic differences in concentrations reveal that sources occur predominantly

KEY CONCEPTS

- Scientists are confident that humans have interfered with the climate and that further human-induced climate change is on the way.
- The principal driver of recent climate change is greenhouse gas emissions from human activities, primarily the burning of fossil fuels.
- The report of the Intergovernmental Panel on Climate Change places the probability that global warming has been caused by human activities at greater than 90 percent. The previous report, published in 2001, put the probability at higher than 66 percent.
- Although further changes in the world's climate are now inevitable, the future, particularly in the longer term, remains largely in our hands—the magnitude of expected change depends on what humans choose to do about greenhouse gas emissions.

—The Editors

TOM DRAPER DESIGN; *left to right:* JOHN MCCONNICO *AP Photo;* JAAP HART *iStockPhoto;* ISTOCKPHOTO; MALCOLM ROMAIN *iStockPhoto;* TONY TREMBLAY *iStockPhoto;* ROB HILL *iStockPhoto*

over land in the more heavily populated Northern Hemisphere. Second, analysis of isotopes, which can distinguish among sources of emissions, demonstrates that the majority of the increase in carbon dioxide comes from combustion of fossil fuels (coal, oil and natural gas). Methane and nitrous oxide increases derive from agricultural practices and the burning of fossil fuels.

Climate scientists use a concept called radiative forcing to quantify the effect of these increased concentrations on climate. Radiative forcing is the change that is caused in the global energy balance of the earth relative to preindustrial times. (Forcing is usually expressed as watts per square meter.) A positive forcing induces warming; a negative forcing induces cooling. We can determine the radiative forcing associated with the long-lived greenhouse gases fairly precisely, because we know their atmospheric concentrations, their spatial distribution and the physics of their interaction with radiation.

Climate change is not driven just by increased greenhouse gas concentrations; other mechanisms—both natural and human-induced—also play a part. Natural drivers include changes in solar activity and large volcanic eruptions. The report identifies several additional significant human-induced forcing mechanisms—microscopic particles called aerosols, stratospheric and tropospheric ozone, surface albedo (reflectivity) and aircraft contrails—although the influences of these mechanisms are much less certain than those of greenhouse gases [*see left illustration in box on opposite page*].

Investigators are least certain of the climatic influence of something called the aerosol cloud albedo effect, in which aerosols from human origins interact with clouds in complex ways and make the clouds brighter, reflecting sunlight back to space. Another source of uncertainty comes from the direct effect of aerosols from human origins: How much do they reflect and absorb sunlight directly as particles? Overall these aerosol effects promote cooling that could offset the warming effect of long-lived greenhouse gases to some extent. But by how much? Could it overwhelm the warming? Among the advances achieved since the 2001 IPCC report is that scientists have quantified the uncertainties associated with each individual forcing mechanism through a combination of many modeling and observational studies. Consequently, we can now confidently estimate the total human-induced component. Our best estimate is some 10 times larger than the best estimate of the natural radiative forcing caused by changes in solar activity.

This increased certainty of a net positive radiative forcing fits well with the observational evidence of warming discussed next. These forcings can be visualized as a tug-of-war, with positive forcings pulling the earth to a warmer climate and negative ones pulling it to a cooler state. The result is a no contest; we know the strength of the competitors better than ever before. The earth is being pulled to a warmer climate and will be pulled increasingly in this direction as the "anchorman" of greenhouse warming continues to grow stronger and stronger.

Observed Climate Changes

The many new or improved observational data sets that became available in time for the 2007 IPCC report allowed a more comprehensive assessment of changes than was possible in earlier reports. Observational records indicate that 11 of the past 12 years are the warmest since reliable records began around 1850. The odds of such warm years happening in sequence purely by chance are exceedingly small. Changes in three important quantities—global temperature, sea level and snow cover in the Northern Hemisphere [*see box on page 68*]—all show evidence of warming, although the details vary. The previous IPCC assessment reported a warming trend of 0.6 ± 0.2 degree Celsius over the period 1901 to 2000. Because of the strong recent warming, the updated trend over 1906 to 2005 is now 0.74 ± 0.18 degree C. Note that the 1956 to 2005 trend alone is 0.65 ± 0.15 degree C, emphasizing that the majority of 20th-century warming occurred in the past 50 years. The climate, of course, continues to vary around the increased averages, and extremes have changed consistently with these averages—frost days and cold days and nights have become less common, while heat waves and warm days and nights have become more common.

The properties of the climate system include not just familiar concepts of averages of temperature, precipitation, and so on but also the state of the ocean and the cryosphere (sea ice, the great ice sheets in Greenland and Antarctica, glaciers, snow, frozen ground, and ice on lakes and rivers). Complex interactions among differ-

JARGON BUSTER

RADIATIVE FORCING, as used in the box on the opposite page, is the change in the energy balance of the earth from preindustrial times to the present.

LONG-LIVED GREENHOUSE GASES include carbon dioxide, methane, nitrous oxide and halocarbons. The observed increases in these gases are the result of human activity.

OZONE is a gas that occurs both in the earth's upper atmosphere and at ground level. At ground level ozone is an air pollutant. In the upper atmosphere, an ozone layer protects life on the earth from the sun's harmful ultraviolet rays.

SURFACE ALBEDO is the reflectivity of the earth's surface: a lighter surface, such as snow cover, reflects more solar radiation than a darker surface does.

AEROSOLS are airborne particles that come from both natural (dust storms, forest fires, volcanic eruptions) and man-made sources, such as the burning of fossil fuels.

CONTRAILS, or vapor trails, are condensation trails and artificial clouds made by the exhaust of aircraft engines.

TROPOSPHERE is the layer of the atmosphere close to the earth. It rises from sea level up to about 12 kilometers (7.5 miles).

STRATOSPHERE lies just above the troposphere and extends upward about 50 kilometers.

TOM DRAPER DESIGN; ISTOCKPHOTO; MIGUEL ANGELO SILVA/*iStockPhoto*; DLILLC/*Corbis*; EMILY HARRISON; DAVID WOODS/*iStockPhoto*; BEN CONLAN/*iStockPhoto*; BETTMANN/CORBIS; ANNA PUSTOVAYA/*iStockPhoto*; NOAA; ISTOCKPHOTO; HEIKO BENNEWITZ/*iStockPhoto*

ent parts of the climate system are a fundamental part of climate change—for example, reduction in sea ice increases the absorption of heat by the ocean and the heat flow between the ocean and the atmosphere, which can also affect cloudiness and precipitation.

A large number of additional observations are broadly consistent with the observed warming and reflect a flow of heat from the atmosphere into other components of the climate system. Spring snow cover, which decreases in concert with rising spring temperatures in northern midlatitudes, dropped abruptly around 1988 and has remained low since. This drop is of concern because snow cover is important to soil moisture and water resources in many regions.

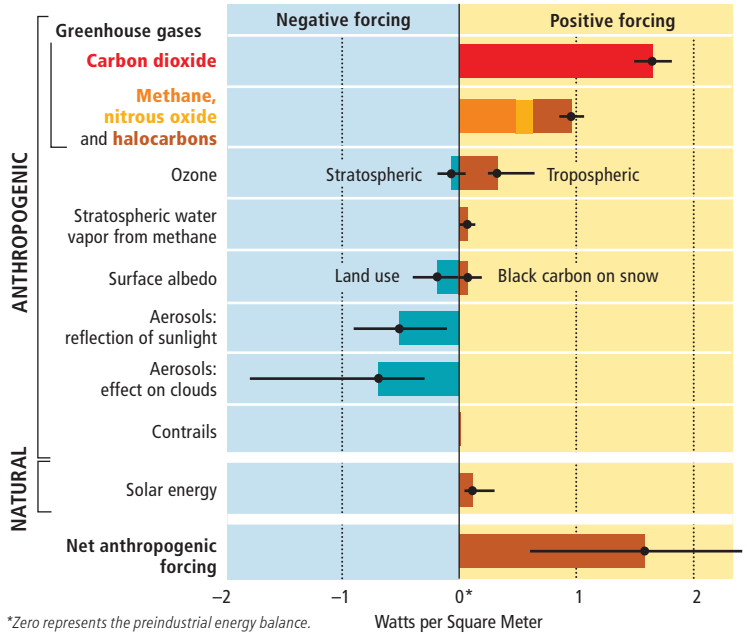
In the ocean, we clearly see warming trends, which decrease with depth, as expected. These changes indicate that the ocean has absorbed more than 80 percent of the heat added to the climate system: this heating is a major contributor to sea-level rise. Sea level rises because water expands as it is warmed and because water from melting glaciers and ice sheets is added to the oceans. Since 1993 satellite observations have permitted more precise calculations of global sea-level rise, now estimated to be 3.1 ± 0.7 millimeters per year over the period 1993 to 2003. Some previous decades displayed similarly fast rates, and longer satellite records will be needed to determine unambiguously whether sea-level rise is accelerating. Substantial reductions in the extent of Arctic sea ice since 1978 (2.7 ± 0.6 percent per decade in the annual average, 7.4 ± 2.4 percent per decade for summer), increases in permafrost temperatures and reductions in glacial extent globally and in Greenland and Antarctic ice sheets have also been observed in recent decades. Unfortunately, many of these quantities were not well monitored until recent de-

Concentrations of carbon dioxide in the atmosphere today are roughly 35 percent above preindustrial levels.

INFLUENCES ON CLIMATE

A tug-of-war between positive forcings (influences that cause the climate to grow warmer) and negative forcings (those that cause it to grow cooler) is a hands-down "victory" for the predominantly human-induced forces that lead to warming (*left graph*). The dominant human-induced forcings are from the long-lived greenhouse gases in the atmosphere, whose concentrations have soared in the past 200 years or so (*right graphs*).

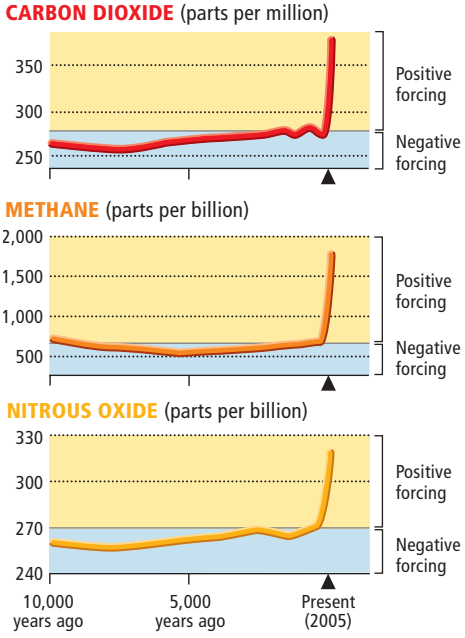
Radiative Forcing: The Overview



*Zero represents the preindustrial energy balance.

Estimates for global averages of radiative forcing in 2005 are shown for the major mechanisms. The black error bars indicate the level of certainty associated with each forcing: it is 90 percent likely that values lie within the error bars. The radiative forcing of the greenhouse gases, for example, is quite certain, as opposed to the uncertainty associated with the aerosol effects. (Volcanic aerosols are not included in the graph because of their episodic nature.)

Greenhouse Gases: The Major Forcings

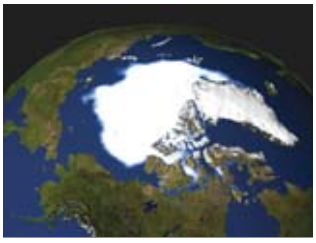


Carbon dioxide, methane and nitrous oxide concentrations of the past were derived from ice cores; those for recent times come from samples of the atmosphere. Large recent increases can be attributed to human activities.

DANIELA NAOMI MOLNAR (*graphs*)

The extent of Arctic sea ice has shrunk substantially.

Arctic sea ice, 1979



Arctic sea ice, 2005

cades, so the starting points of their records vary.

Hydrological changes are broadly consistent with warming as well. Water vapor is the strongest greenhouse gas; unlike other greenhouse gases, it is controlled principally by temperature. It has generally increased since at least the 1980s. Precipitation is very variable locally but has increased in several large regions of the world, including eastern North and South America, northern Europe, and northern and central Asia. Drying has been observed in the Sahel, the Mediterranean, southern Africa and parts of southern Asia. Ocean salinity can act as a massive rain gauge. Near-surface waters of the oceans have generally freshened in middle and high latitudes, while they have become saltier in lower latitudes, consistent with changes in large-scale patterns of precipitation.

Reconstructions of past climate—paleoclimate—from tree rings and other proxies provide important additional insights into the workings of the climate system with and without human influence. They indicate that the warmth of the past half a century is unusual in at least the previous 1,300 years. The warmest period between A.D. 700 and 1950 was probably A.D. 950 to 1100, which was several tenths of a degree C cooler than the average temperature since 1980.

Attribution of Observed Changes

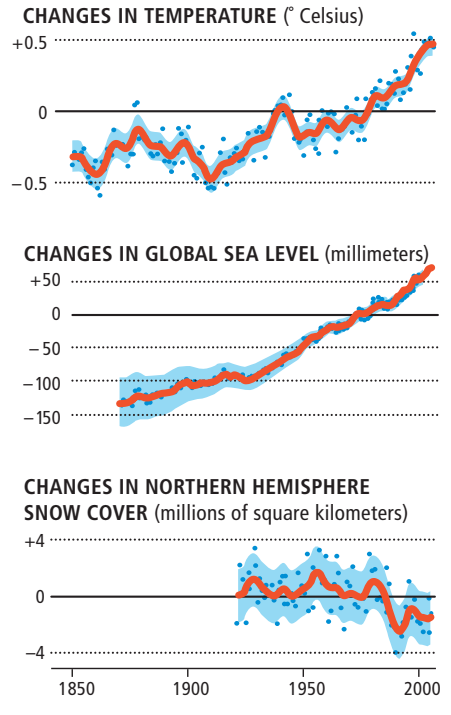
Although confidence is high both that human activities have caused a positive radiative forcing and that the climate has actually changed, can we confidently link the two? This is the question of attribution: Are human activities primarily responsible for observed climate changes, or is it possible they result from some other cause, such as some natural forcing or simply spontaneous variability within the climate system? The 2001 IPCC report concluded it was *likely* (more than 66 percent probable) that most of the warming since the mid-20th century was attributable to humans. The 2007 report goes significantly further, upping this to *very likely* (more than 90 percent probable).

The source of the extra confidence comes from a multitude of separate advances. For a start, observational records are now roughly five years longer, and the global temperature increase over this period has been largely consistent with IPCC projections of greenhouse gas–driven warming made in previous reports dating back to 1990. In addition, changes in more aspects of the climate have been considered, such as those in atmospheric circulation or in temperatures within the ocean. Such changes paint a consistent and now broadened picture of human intervention. Climate models, which are central to attribution studies, have also improved and are able to represent the current climate and that of the recent past with considerable fidelity. Finally, some important apparent inconsistencies noted in the observational record have been largely resolved since the last report.

The most important of these was an apparent mismatch between the instrumental surface temperature record (which showed significant warming over recent decades, consistent with a human impact) and the balloon and satellite atmospheric records (which showed little of the expected warming). Several new studies of the satellite and balloon data have now largely re-

OBSERVED EVIDENCE

Observations of global average surface temperature, sea level and snow cover for the Northern Hemisphere in March and April document increased warming. Red lines represent values averaged over a decade, with the blue shading indicating the range of uncertainty; blue dots show yearly values. All measures are relative to 1961–1990.



NASA GODDARD SPACE FLIGHT CENTER SCIENTIFIC VISUALIZATION STUDIO (*Arctic sea ice images*); TOM DRAPER DESIGN; STEPHEN STRATHDEE *iStockPhoto*; ISTOCKPHOTO; MARTIN BOND *Photo Researchers, Inc.*; BETTMANN/CORBIS; NICK TZOLOV *iStockPhoto*; JEREMY EDWARDS *iStockPhoto*; ISTOCKPHOTO; HASAN KURSAD ERGAN *iStockPhoto*; JIM REED *JPN/Aurora Photos*; BETTMANN/CORBIS; RICK RHAY *iStockPhoto*

solved this discrepancy—with consistent warming found at the surface and in the atmosphere.

An experiment with the real world that duplicated the climate of the 20th century with constant (rather than increasing) greenhouse gases would be the ideal way to test for the cause of climate change, but such an experiment is of course impossible. So scientists do the next best thing: they simulate the past with climate models.

Two important advances since the last IPCC assessment have increased confidence in the use of models for both attribution and projection of climate changes. The first is the development of a comprehensive, closely coordinated ensemble of simulations from 18 modeling groups around the world for the historical and future evolution of the earth's climate. Using many models helps to quantify the effects of uncertainties in various climate processes on the range of model simulations. Although some processes are well understood and well represented by physical equations (the flow of the atmosphere and ocean or the propagation of sunlight and heat, for example), some of the most critical components of the climate system are less well understood, such as clouds, ocean eddies and transpiration by vegetation. Modelers approximate these components using simplified representations called parameterizations. The principal reason to develop a multimodel ensemble for the IPCC assessments is to understand how this lack of certainty affects attribution and prediction of climate change. The ensemble for the latest assessment is unprecedented in the number of models and experiments performed.

The second advance is the incorporation of more realistic representations of climate processes in the models. These processes include the behavior of atmospheric aerosols, the dynamics (movement) of sea ice, and the exchange of water and energy between the land and the atmosphere. More models now include the major types of aerosols and the interactions between aerosols and clouds.

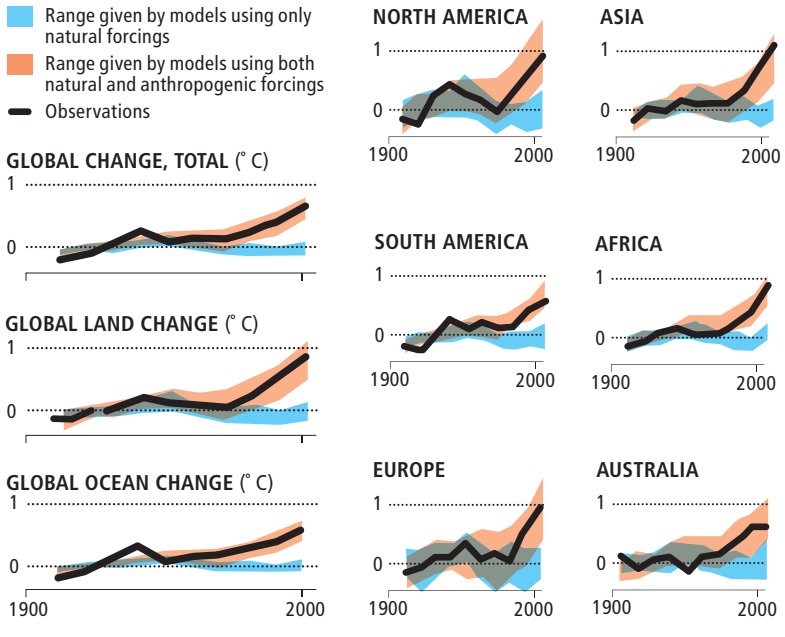
When scientists use climate models for attribution studies, they first run simulations with estimates of only "natural" climate influences over the past 100 years, such as changes in solar output and major volcanic eruptions. They then run models that include human-induced increases in greenhouse gases and aerosols. The results of such experiments are striking [*see box below*]. Models using only natural forcings are unable to explain the observed global warming since the mid-20th century, whereas they can do so when they include anthropogenic factors in addition to natural ones. Large-scale *patterns* of temperature change are also most consistent between models and observations when all forcings are included.

Two patterns provide a fingerprint of human influence. The first is greater warming over land than ocean and greater warming at the surface of the sea than in the deeper layers. This pattern is consistent with greenhouse gas–induced warming by the overlying atmosphere: the ocean warms more slowly because of its large thermal inertia. The warming also indicates that a large amount of heat is being taken up by the ocean, demonstrating that the planet's energy budget has been pushed out of balance. A second pattern of change is that while the troposphere (the lower region of the atmosphere) has warmed, the stratosphere, just above it, has cooled. If solar changes provided the dominant forcing, warming would be expected in both atmospheric layers. The

Eleven of the past 12 years are the warmest since reliable records began around 1850.

HUMAN-INDUCED TEMPERATURE CHANGE

Models using only natural forcings (*blue*) do not reflect the actual increases in temperature. When both natural and human-induced forcings (*orange*) are included, however, the models reproduce the real-world rise in temperature, both on a global scale and on a continental scale. Changes are shown relative to the average for 1901–1950.



LUCY READING-IKKANDA (*graphs on this page and opposite page*)

observed contrast, however, is just that expected from the combination of greenhouse gas increases and stratospheric ozone decreases. This collective evidence, when subjected to careful statistical analyses, provides much of the basis for the increased confidence that human influences are behind the observed global warming. Suggestions that cosmic rays could affect clouds, and thereby climate, have been based on correlations using limited records; they have generally not stood up when tested with additional data, and their physical mechanisms remain speculative.

What about at smaller scales? As spatial and temporal scales decrease, attribution of climate change becomes more difficult. This problem arises because natural small-scale temperature variations are less "averaged out" and thus more readily mask the change signal. Nevertheless, continued warming means the signal is emerging on smaller scales. The report has found that human activity is likely to have influenced temperature significantly down to the continental scale for all continents except Antarctica.

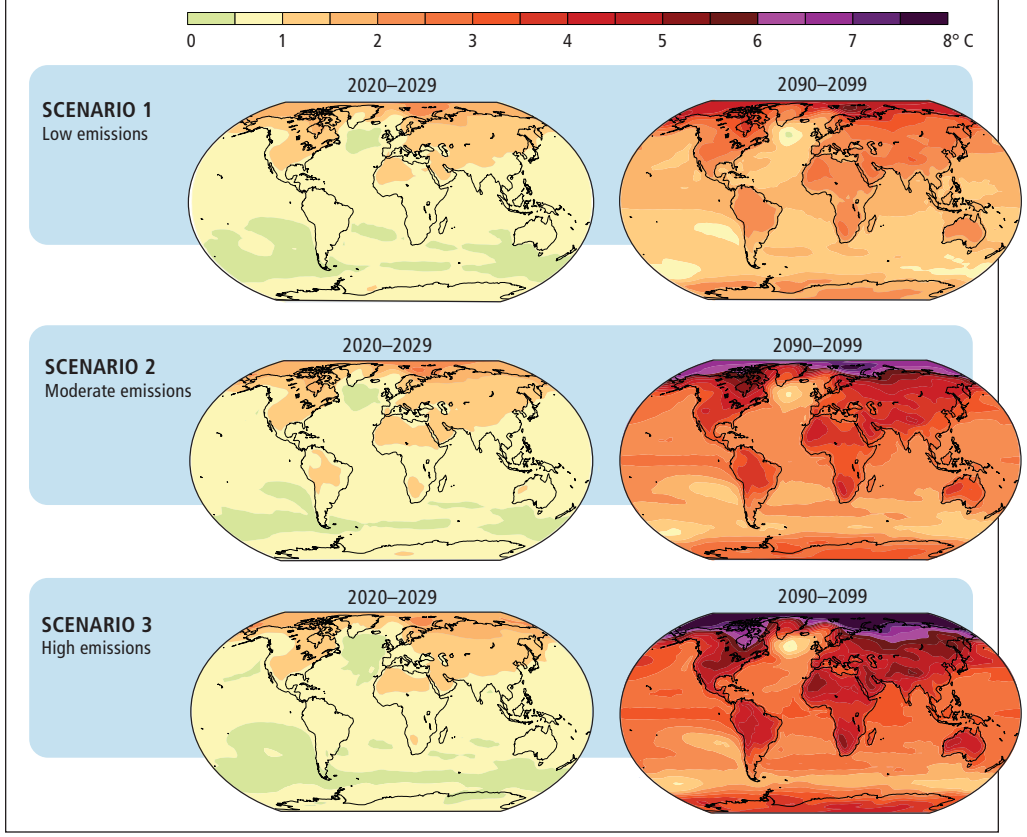
Human influence is discernible also in some extreme events such as unusually hot and cold nights and the incidence of heat waves. This does not mean, of course, that individual extreme events (such as the 2003 European heat wave) can be said to be simply "caused" by human-induced climate change—usually such events are complex, with many causes. But it does mean that human activities have, more likely than not, affected the *chances* of such events occurring.

Projections of Future Changes

How will climate change over the 21st century? This critical question is addressed using simulations from climate models based on projections of future emissions of greenhouse gases and aerosols. The simulations suggest that, for greenhouse gas emissions at or above current

PROJECTED TEMPERATURE CHANGES

Projected changes in surface temperature (relative to 1980–1999), based on 22 models from 17 different programs, were calculated for three socioeconomic scenarios. All three scenarios are based on studies made before 2000 and assume no additional climate policy; in other words, they are not mitigation scenarios.



DANIELA NAOMI MOLNAR; SOURCE: *CLIMATE CHANGE 2007: THE SCIENTIFIC BASIS, SUMMARY FOR POLICYMAKERS*, INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (*maps*); TOM DRAPER DESIGN; ISTOCKPHOTO; TY MILFORD *Aurora Photos*; LINDSAY HEBBERD *Corbis*; BILDERBUCH *Design Pics/Corbis*; DANIEL STEIN *iStockPhoto*; OLEG FEDORENKO *iStockPhoto*; PETER ESSICK *Aurora Photos*; SHAUN LOWE *iStockPhoto*; BURCU ARAT SUP *iStockPhoto*

[THE AUTHORS]

The authors were participants in Working Group I of the 2007 IPCC assessment. William Collins is a professor in residence in the department of earth and planetary science at the University of California, Berkeley, and a senior scientist at Lawrence Berkeley National Laboratory and the National Center for Atmospheric Research in Boulder, Colo. Robert Colman is a senior research scientist in the Climate Dynamics Group at the Australian Bureau of Meteorology Research Center in Melbourne. James Haywood is the manager of aerosol research in the Observational Based Research Group and the Chemistry, Climate and Ecosystem Group at the Met Office in Exeter, England. Martin R. Manning is director of the IPCC WG I Support Unit at the NOAA Earth System Research Laboratory in Boulder, Colo. Philip Mote is the Washington State climatologist, a research scientist in the Climate Impacts Group at the University of Washington, and an affiliate professor in the department of atmospheric sciences.

rates, changes in climate will very likely be larger than the changes already observed during the 20th century. Even if emissions were immediately reduced enough to stabilize greenhouse gas concentrations at current levels, climate change would continue for centuries. This inertia in the climate results from a combination of factors. They include the heat capacity of the world's oceans and the millennial timescales needed for the circulation to mix heat and carbon dioxide throughout the deep ocean and thereby come into equilibrium with the new conditions.

To be more specific, the models project that over the next 20 years, for a range of plausible emissions, the global temperature will increase at an average rate of about 0.2 degree C per decade, close to the observed rate over the past 30 years. About half of this near-term warming represents a "commitment" to future climate change arising from the inertia of the climate system response to current atmospheric concentrations of greenhouse gases.

The long-term warming over the 21st century, however, is strongly influenced by the future rate of emissions, and the projections cover a wide variety of scenarios, ranging from very rapid to more modest economic growth and from more to less dependence on fossil fuels. The best estimates of the increase in global temperatures range from 1.8 to 4.0 degrees C for the various emission scenarios, with higher emissions leading to higher temperatures. As for regional impacts, projections indicate with more confidence than ever before that these will mirror the *patterns* of change observed over the past 50 years (greater warming over land than ocean, for example) but that the *size* of the changes will be larger than they have been so far.

The simulations also suggest that the removal of excess carbon dioxide from the atmosphere by natural processes on land and in the ocean will become less efficient as the planet warms. This change leads to a higher percentage of emitted carbon dioxide remaining in the atmosphere, which then further accelerates global warming. This is an important positive feedback on the carbon cycle (the exchange of carbon compounds throughout the climate system). Although models agree that carbon-cycle changes represent a positive feedback, the range of their responses remains very large, depending, among other things, on poorly understood changes in vegetation or soil uptake of carbon as the climate warms. Such processes are an important topic of ongoing research.

The models also predict that climate change will affect the physical and chemical characteristics of the ocean. The estimates of the rise in sea level during the 21st century range from about 30 to 40 centimeters, again depending on emissions. More than 60 percent of this rise is caused by the thermal expansion of the ocean. Yet these model-based estimates do not include the possible acceleration of recently observed increases in ice loss from the Greenland and Antarctic ice sheets. Although scientific understanding of such effects is very limited, they could add an additional 10 to 20 centimeters to sea-level rises, and the possibility of significantly larger rises cannot be excluded. The chemistry of the ocean is also affected, as the increased concentrations of atmospheric carbon dioxide will cause the ocean to become more acidic.

Some of the largest changes are predicted for polar regions. These include significant increases in high-latitude land temperatures and in the depth of thawing in permafrost regions and sharp reductions in the extent of summer sea ice in the Arctic basin. Lower latitudes will likely experience more heat waves, heavier precipitation, and stronger (but perhaps less frequent) hurricanes and typhoons. The extent to which hurricanes and typhoons may strengthen is uncertain and is a subject of much new research.

Some important uncertainties remain, of course. For example, the precise way in which clouds will respond as temperatures increase is a critical factor governing the overall size of the projected warming. The complexity of clouds, however, means that their response has been frustratingly difficult to pin down, and, again, much research remains to be done in this area.

We are now living in an era in which both humans and nature affect the future evolution of the earth and its inhabitants. Unfortunately, the crystal ball provided by our climate models becomes cloudier for predictions out beyond a century or so. Our limited knowledge of the response of both natural systems and human society to the growing impacts of climate change compounds our uncertainty. One result of global warming is certain, however. Plants, animals and humans will be living with the consequences of climate change for at least the next thousand years.

THE MECHANICS OF THE IPCC

The IPCC was established by governments in 1988 to provide assessments of available scientific and technical information on climate change. The process used to produce these assessments is designed to ensure their high credibility in both science and policy communities.

Comprehensive assessments were published in 1990, 1995, 2001 and 2007.

Three separate "working groups" examine the physical science of climate change, the effects on nature and society, and methods for mitigation.

Lead authors, who are active participants in relevant research, are nominated by governments. Care is taken to balance points of view as well as geography, gender and age.

A review process tests the authors' assessment against views in the broader expert community. More than 600 expert reviewers provided over 30,000 comments on the report of Working Group I, on which this article is based.

Each of the three working groups also issues a "Summary for Policymakers," which is done in cooperation with government delegates to ensure that the language used is clear to policymakers.

MORE TO EXPLORE

All IPCC reports and summaries are available at www.ipcc.ch

More information from the authors is available at www.SciAm.com/ontheweb

FACING OUR FUTURE: Notes from the Editors

THE CONSEQUENCES OF ONGOING WARMING

Global warming is real and, as Working Group I of the IPCC stated in its January–February 2007 report, "very likely" to be largely the result of human activities for at least the past half a century. But is that warming significant enough to pose real problems? That determination fell to Working Group II, a similarly international assembly of scientists who focused on the vulnerability of natural and human environments to climate change.

In the April 2007 summary of its findings, Working Group II concluded that human-induced warming over the past three and a half decades has indeed had a discernible influence on many physical and biological systems. Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases. The ground in permafrost regions is becoming increasingly unstable, rock avalanches in mountainous areas are more frequent, trees are coming into leaf earlier, and some animals and plants are moving to higher latitudes or elevations.

Looking to the future, the group also projected that ongoing shifts in climate would affect the health and welfare of millions of people around the world. The severity of the effects would depend on precisely how much warming occurred. Among the most probable consequences:

- More frequent heat waves, droughts, fires, coastal flooding and storms will raise the toll of deaths, injuries and related diseases.
- Some infectious diseases, such as malaria, will spread to new regions.
- High concentrations of ground-level ozone will exacerbate heart and respiratory ailments.
- By the 2080s, rising sea levels will flood the homes and property of millions of people, especially in the large deltas of Asia and Africa and on small islands.

The harm from these changes will be most severe for impoverished communities. The poor are generally more dependent on climate-sensitive resources such as local water and food, and by definition their adaptive capacities are economically limited.

The effects of global warming would not be universally bad, particularly for the next few decades. For example, whereas higher temperatures would hurt the growth of important cereals in equatorial nations fairly quickly, they would for a time raise productivity on farms in mid- to high-latitude countries, such as the U.S. But once the temperature increase exceeded three degrees Celsius (5.4 degrees Fahrenheit), agricultural declines would set in even there, barring widespread adaptive changes.

Central and South America

- Gradual replacement of tropical forest by savanna in eastern Amazonia
- Replacement of semiarid vegetation by arid-land vegetation
- Species extinctions in many tropical areas
- Reduced water availability
- Loss of arable land in drier areas
- Decreased yields of some important crops
- Reduced livestock productivity

WHAT NEEDS TO BE DONE

The human race can respond to climate change in two ways: adaptation and mitigation. Adaptation means learning how to survive and prosper in a warmer world. Mitigation means limiting the extent of future warming by reducing the net release of greenhouse gases to the atmosphere. Given that rising temperatures are already encroaching on us and that an unstopped increase would be overwhelming, a strong combination of both adaptation and mitigation will be essential. Unfortunately, disagreements over the feasibility, costs and necessity of mitigation have notoriously bogged down global responses to date.

To project mitigation strategies for the looming problems—and their costs—Working Group III of the IPCC considered various estimates of economic expansion, population growth and fossil-fuel use for its 2007 report. The six resulting scenarios predict atmospheric concentrations of carbon dioxide equivalents (that is, greenhouse gases and aerosols equivalent to carbon dioxide) ranging from 445 parts per million to 1,130 ppm, with corresponding increases in temperatures from 2.0 to as much as 6.1 degrees C (approximately 3.6 to 11 degrees F) over preindustrial levels. To keep the temperature increase to the lowest of those projections, the group estimates that the world must stabilize atmospheric greenhouse gases at 445 ppm by 2015. (Current concentrations are approaching 400 ppm.) The scientists believe that any higher temperatures might trigger severe flooding in some places and severe drought in others, wipe out species and cause economic havoc.

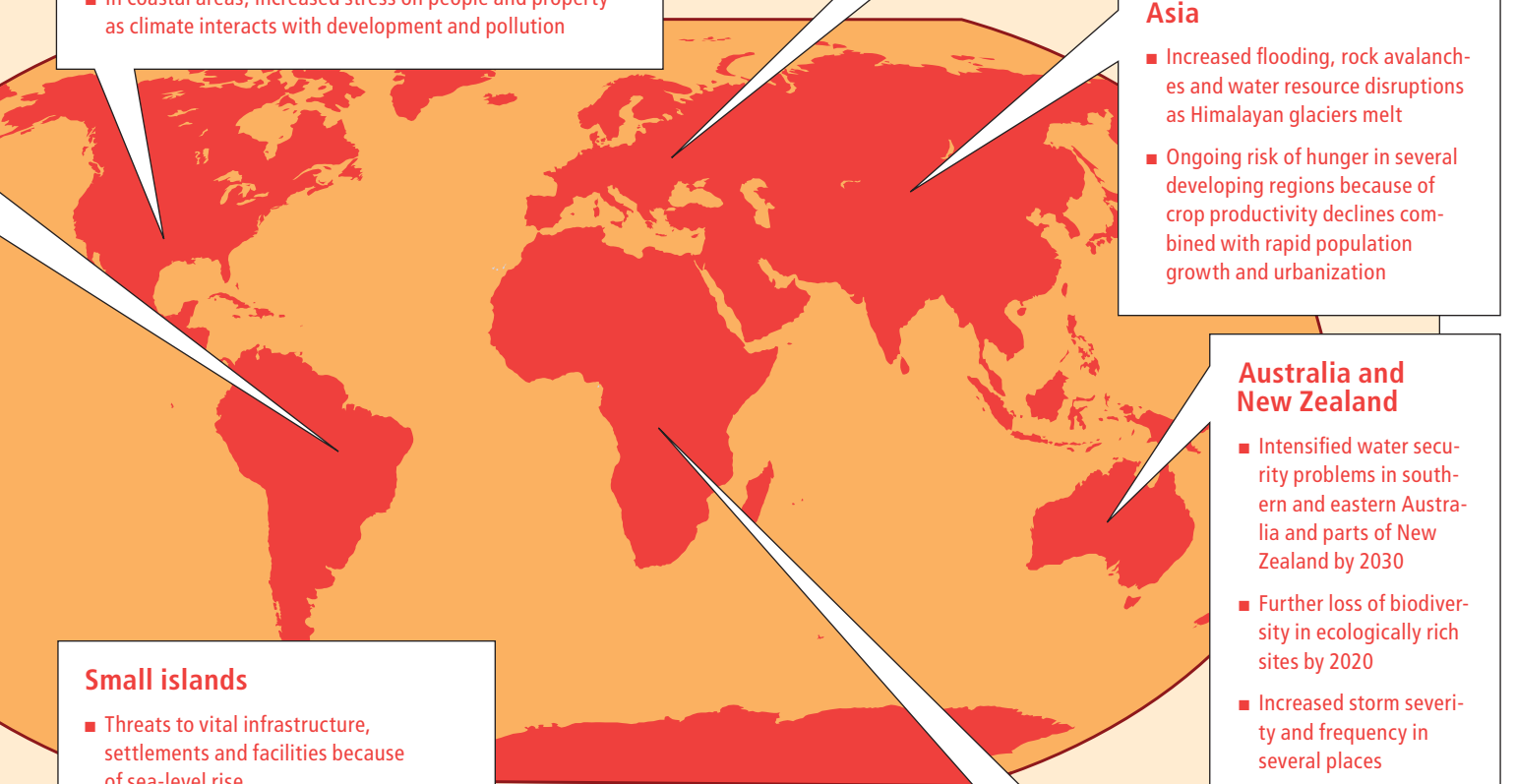
The group's report looks in detail at the most promising technologies and policies for holding the gases at 445 ppm. It emphasizes the importance of improving energy efficiency in buildings and vehicles, shifting to renewable energy sources and saving forests as "carbon sinks." Policies include setting a target for global emissions, emissions trading schemes, caps, taxes and incentives.

But the IPCC scientists made their assessment before a study published online this past April in the *Proceedings of the National Academy of Sciences USA* reported that worldwide carbon dioxide emissions between 2000 and 2004 increased at three times the rate of the 1990s—from 1.1 to 3.2 percent a year. In other words, the actual global emissions since 2000 grew faster than those projected in the highest of the scenarios developed by the IPCC. That research indicates that the situation is more dire than even the bleak IPCC assessment forecasts.

DANIELA NAOMI MOLNAR (*map*); SOURCE: UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH (UCAR) AND IPCC

The Regional Picture

The lists here indicate just some of the disturbing effects, beyond those enumerated in the discussion at the left, that Working Group II foresees in various parts of the world over the coming century. The group made most of these predictions with high or very high confidence. Find more details at www.ucar.edu/news/features/climatechange/regionalimpacts.jsp and at the IPCC Web site (www.ipcc.ch).



North America

- In the western mountains, decreased snowpack, more winter flooding and reduced summer flows
- An extended period of high fire risk and large increases in area burned
- Increased intensity, duration and number of heat waves in cities historically prone to them
- In coastal areas, increased stress on people and property as climate interacts with development and pollution

Europe

- Increased risk of inland flash floods
- In the south, more health-threatening heat waves and wildfires, reduced water availability and hydropower potential, endangered crop production and reduced summer tourism
- In the central and eastern areas, more health-threatening heat waves and peatland fires and reduced summer rainfall and forest productivity
- In the north, negative impacts eventually outweigh such initial benefits as reduced heating demand and increased crop yields and forest growth

Asia

- Increased flooding, rock avalanches and water resource disruptions as Himalayan glaciers melt
- Ongoing risk of hunger in several developing regions because of crop productivity declines combined with rapid population growth and urbanization

Australia and New Zealand

- Intensified water security problems in southern and eastern Australia and parts of New Zealand by 2030
- Further loss of biodiversity in ecologically rich sites by 2020
- Increased storm severity and frequency in several places

Small islands

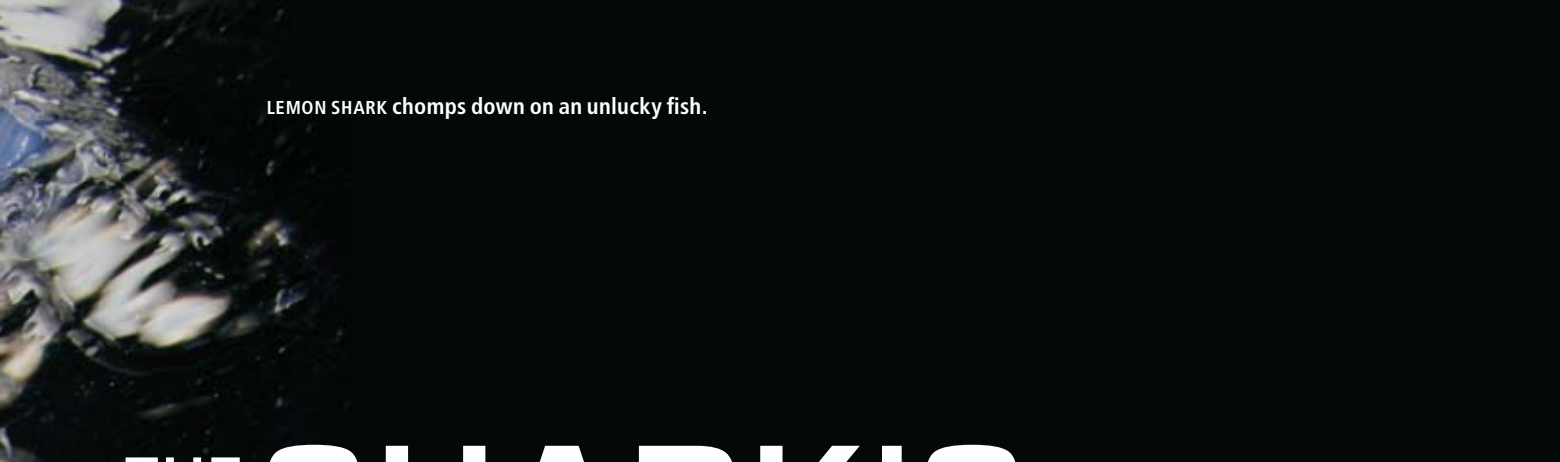
- Threats to vital infrastructure, settlements and facilities because of sea-level rise
- Reduced water resources in many places by midcentury
- Beach erosion, coral bleaching and other deteriorating coastal conditions, leading to harmed fisheries and reduced value as tourist destinations
- Invasion by nonnative species, especially on mid- and high-latitude islands

Polar regions

- Thinning and shrinking of glaciers and ice sheets
- Changes in the extent of Arctic sea ice and permafrost
- Deeper seasonal thawing of permafrost

Africa

- Decreased water availability by 2020 for 75 million to 250 million people
- Loss of arable land, reduced growing seasons and reduced yields in some areas
- Decreased fish stocks in large lakes



LEMON SHARK chomps down on an unlucky fish.

THE SHARK'S ELECTRIC SENSE

An astonishingly sensitive detector of electric fields helps sharks zero in on prey

By R. Douglas Fields

A menacing fin pierced the surface and sliced toward us. A great blue shark—three meters in length—homed in on the scent of blood like a torpedo. As my wife, Melanie, and I watched several large sharks circle our seven-meter Boston Whaler, a silver-blue snout suddenly thrust through a square cutout in the boat deck. "Look out!" Melanie shouted. We both recoiled instinctively, but we were in no real danger. The shark flashed a jagged smile of ivory saw teeth and then slipped back into the sea.

We had drawn the sharks by ladling blood into the ocean, but we were not interested in their well-known attraction to blood. Rather we were investigating the hunters' mysterious "sixth sense." Laboratory research had demonstrated that sharks can sense extremely weak electric fields—such as those animal cells produce when in contact with seawater. But how they use that unique sense had yet to be proved. We were on that boat to find out.

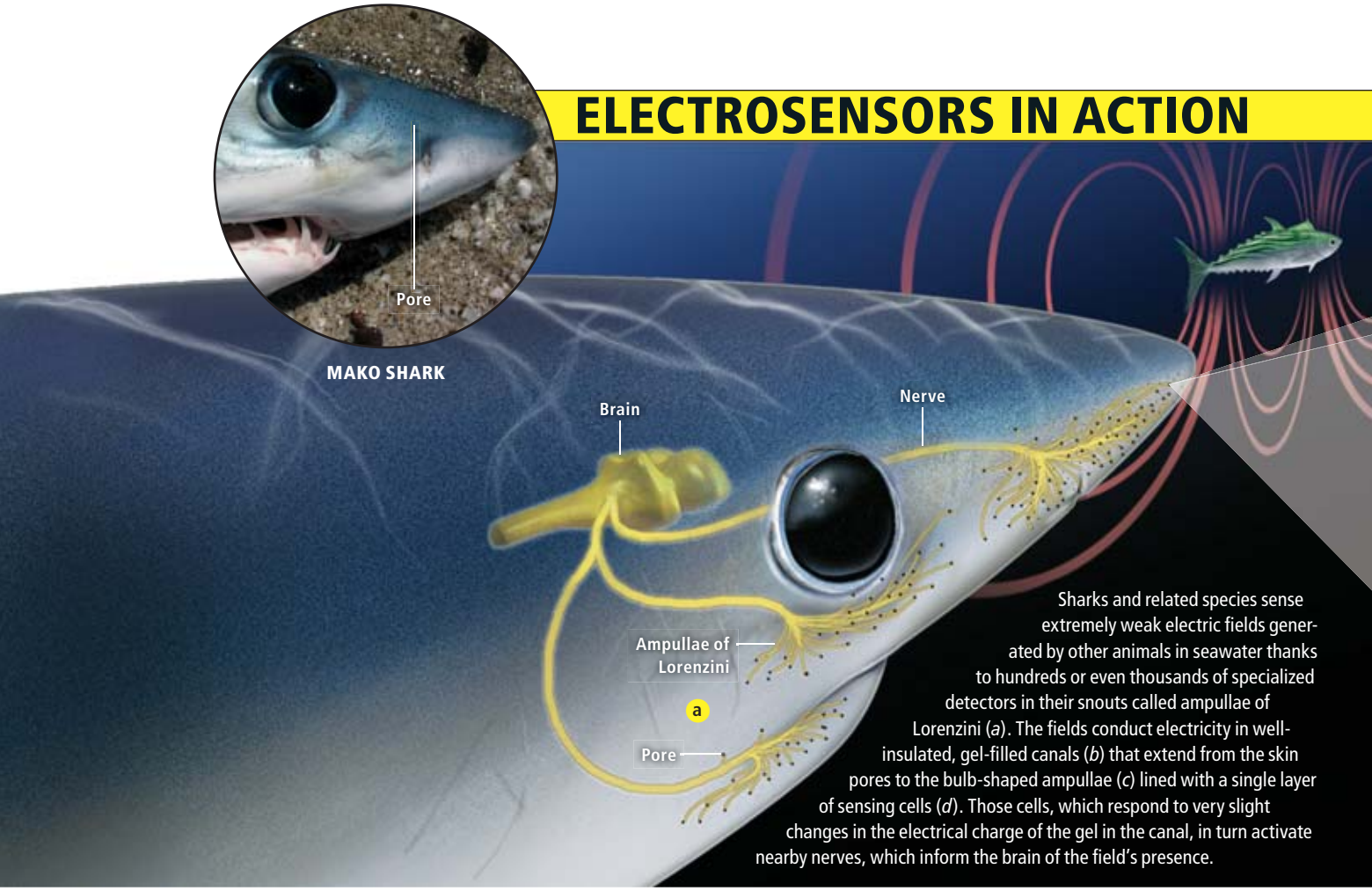
Until the 1970s, scientists did not even suspect that sharks could perceive weak electric fields. Today we know that such electroreception helps the fish find food and can operate even when environmental conditions render the five common senses—sight, smell, taste, touch, hearing—all but useless. It works in turbid water, total darkness and even when prey hide beneath the sand.

My research colleagues and I are now exploring the molecular basis for this ability, while others pursue such questions as how the sensing organ forms during development and whether our own vertebrate ancestors once could detect electric fields before they left the sea. All this work is still

KEY CONCEPTS

- Sharks and related fish can sense the extremely weak electric fields emitted by animals in the surrounding water, an ability few other organisms possess.
- This ability is made possible by unique electrosensory structures called ampullae of Lorenzini, after the 17th-century anatomist who first described them.
- The author and his colleagues have demonstrated that sharks use this "sixth sense" to home in on prey during the final phase of an attack. Other potential uses for electroreceptors remain to be determined.

—The Editors



ONE MILLIONTH OF A VOLT ACROSS A CENTIMETER OF SEAWATER

can be distinguished by a shark. This is equivalent to a voltage gradient created by a 1.5-volt AA battery with one pole dipped in the Long Island Sound and the other pole in waters off Jacksonville, Fla.

quite preliminary, though. Here I describe how investigators first discovered electroreception in sharks and how we demonstrated its importance to successful hunting—a fascinating, little-known tale that spans centuries.

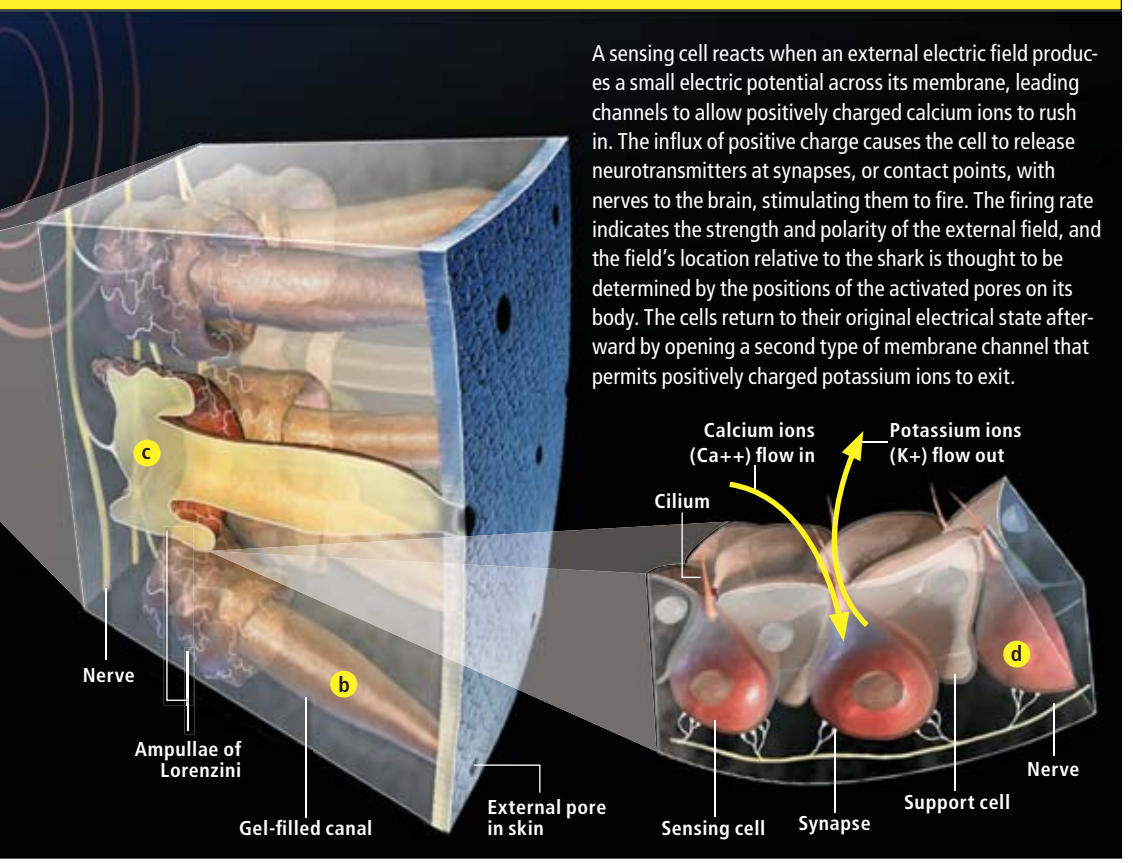
Hidden Sense

The story begins in 1678, when Italian anatomist Stefano Lorenzini described pores that speckled the forward part of the head of sharks and rays, endowing them with something resembling a bad five-o'clock shadow. He noted that the pores concentrated around a shark's mouth and found that if he peeled back the neighboring skin, each opening led to a long transparent tube that was filled with a crystalline gel. Some of the tubes were small and delicate, but others were nearly the diameter of a strand of spaghetti and several inches in length. Deep within the head, Lorenzini discovered, the tubes congregated in several large masses of clear jelly. He considered and then rejected the possibility that these pores were the source of fish body slime. Later, he speculated that the pores might have another, "more hidden function," but their true purpose remained unexplained for hundreds of years afterward.

The pores' purpose started to become clear in the middle of the 19th century, when researchers began to glean the function of the so-called lateral line, an organ that shares some similarities with Lorenzini's pore-and-tube system. The lateral line, a stripe extending down the sides of many fish and amphibians from gills to tail, detects water displacement. In fish, it consists of a specialized row of perforated scales, each of which opens into a tube lying lengthwise just under the skin. At swellings along the length, specialized sensory cells called hair cells extend slender, brushlike projections (or cilia) into the tube. Slight water movements, such as those caused by fish swimming a few feet away, bend the microscopic hair masses like wind-driven waves rippling through a field of grain. This reaction excites nerves, whose impulses inform the brain about the strength and direction of the water displacement. We retain the descendant of this lateral line in our ear cochlea.

By the late 19th century the newly improved microscope revealed that the pores on a shark's snout and the unusual structures underneath them, today called ampullae of Lorenzini, must be sensory organs of some kind. Each tube was

BRANDON COLE (*preceding pages*); AMADEO BACHAR (*photograph and illustration of mako shark snout*)



seen to end in a bulbous pouch, or ampulla. A thin nerve emerged from the ampulla and joined branches of the anterior lateral line nerve. Scientists traced these nerve fibers to the base of the skull, where they enter the brain through the dorsal surface of the medulla, a destination characteristic of nerves that carry sensory information into the brain. Observers discerned a single tiny hair cell, similar to those of the human inner ear and of a fish's lateral line system, inside each ampulla. The type of stimulus they might detect remained unknown, however.

Electroreception Confirmed

Researchers found themselves faced with a dilemma: How could they determine the function of this entirely foreign sense organ? The eventual solution came down to the combination of good instrumentation and a fertile imagination.

In 1909 biologist G. H. Parker of Harvard University removed skin from around the ampullar openings of a dogfish to eliminate any tactile receptors in the area. He then observed that the fish nonetheless reacted when the exposed tubes were touched gently. This response suggested that the organs might sense water motion or perhaps water pressure, but he could not be sure. After all, a reflex reaction to a poke in the eye does not necessarily mean that eyes had evolved to perceive sudden jabs.

Just as microscopes had opened up new research avenues a century before, the just-devised vacuum-tube amplifier advanced the study of brain function in the second quarter of the 20th century. In 1938 Alexander Sand of the Marine Biological Association in Plymouth, England, succeeded in amplifying and recording nerve pulses running from ampullae of Lorenzini to the brain. He saw that impulses shot down the nerve in a steady stream but that certain stimuli caused the rate to increase or decrease suddenly. Sand noticed, as Parker had, that the organs responded to touch or pressure, but he found that the firing rate also rose when cooled. Indeed, the ampullae were so sensitive to temperature that they could detect external changes as small as 0.2 degree Celsius. Such fine discrimination, together with the well-known importance of water temperature to migration and other fish behavior, seemed strong evidence that the organs were temperature receptors.

In the early 1960s biologist R. W. Murray of

TIMELINE: UNDERSTANDING ELECTRORECEPTION

1678: Italian anatomist Stefano Lorenzini describes the structure of the electroreception system of sharks and rays. Its function remains a mystery.

Late 1800s: Scientists explain the function of fish's lateral line, an organ that detects water displacement and in some ways resembles the electroreception system. Examination with microscopes delineates the details of what soon become known as ampullae of Lorenzini.

1909: G. H. Parker finds that the ampullae respond to touch. He speculates that they might sense water motion.

1938: Alexander Sand records nerve impulse output from ampullae of Lorenzini in response to various stimuli. He notices that they react to tiny temperature changes.

1950s: H. W. Lissmann and others describe "tuberous receptors" in weakly electric fish that sense their own fields. The discovery adds electroreception to the list of known animal senses.

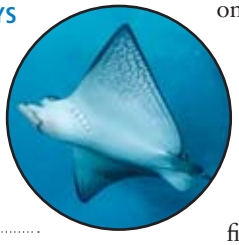
Early 1960s: R. W. Murray finds that ampullae of Lorenzini are sensitive to slight salinity variations and weak electric fields.

1970s: Adrianus Kalmijn determines that in seawater animal bodies produce electric fields. He also demonstrates that captive sharks can locate and attack buried electrodes that emit similar electric fields.

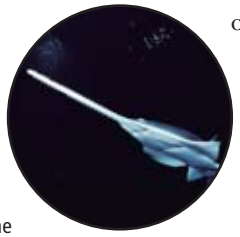
1990s to present: Researchers show that electroreception is an ancient sense that is widespread among aquatic animals.

FISH WITH A SIXTH SENSE

Beyond sharks, several well-known fish have similar ampullary electroreceptors, including:



COMMON RAYS AND SKATES, which glide on enlarged pectoral fin "wings" close to the bottom to feed.



SAWFISH, which have sawlike snouts covered with motion-sensitive and electrosensitive pores that allow them to detect prey buried in the ocean floor.

ELECTRIC RAYS, which have organs that can deliver an electrical discharge to stun or kill prey.

STURGEONS, which use their wedge-shaped snouts and sensitive, whiskerlike barbels to find food in the bottom sediments.

LUNGFISH, which can breathe air and are adapted to fresh, often muddy, water.

the University of Birmingham in England repeated Sand's experiments with modern electrophysiological instruments and confirmed the responses to temperature changes, pressure differences and touch, but he also observed that the organs were sensitive to slight variations in salinity. Moreover, when he happened to switch on an electric field near the opening of a tube connected to an ampulla, the firing pattern changed. Further, the pattern altered according to the intensity and polarity of the field. When the field's positive pole neared the opening of an ampulla, the firing rate declined; when the negative pole came near, firing increased.

Astonishingly, Murray determined that the organs could respond to fields as weak as one millionth of a volt applied across a centimeter of seawater. This effect is equivalent to the intensity of the voltage gradient that would be produced in the sea by connecting up a 1.5-volt AA battery with one pole dipped in the Long Island Sound and the other pole in the waters off Jacksonville, Fla. Theoretically, a shark swimming between these points could easily tell when the battery was switched on or off. (Later measurements of brain response indicate that sharks can discern 15 billionths of a volt.) No other tissue, organ or animal exhibits such extreme sensitivity to electricity. Indeed, engineers have difficulty measuring such weak fields in seawater using modern equipment.

The Search for a Function

What could fish gain by detecting weak electric fields? Hints to the answer came from earlier studies of "bioelectricity"—electric field emissions—by other fish. Electric eels, for example, can stun prey with strong shocks generated by a specialized organ. Certain other fish, however, seem to purposely produce much weaker electric fields too faint to serve as weapons. The evolution of such apparently useless organs puzzled even Charles Darwin, who grappled with this biological riddle in *On the Origin of Species*.

Searching for the function of that weak bioelectricity, zoologist H. W. Lissmann of the University of Cambridge and others in the 1950s found that fish that produced it were able to detect their own electric field. Their sensors, known as tuberous receptors, are very different from ampullae of Lorenzini: they lack the long tubes and are not nearly as sensitive to electric fields. Nevertheless, at the time, their discovery added electroreception to the familiar list of five senses.

Together, weak electric organs and tuberous electroreceptors form the emitter and receiver of a radarlike system that is extremely useful for tasks such as navigating the muddy Amazon River or feeding at night. As objects distort the shape of the emitted electric field, tuberous receptors detect the change, thereby revealing the location of the objects.

Sharks and rays lack dedicated organs for emitting fields, however. Researchers speculated that the acutely sensitive ampullae of Lorenzini might work as a passive "radar" system, detecting feeble electric fields occurring naturally in the environment—much like some night-vision goggles reveal a nighttime battlefield by amplifying starlight.

What, then, were these animals detecting? Possibly they were sensing very brief, weak forms of bioelectricity such as brain waves and heart muscle contraction potentials. But it seemed unlikely that sharks could use their ampullae of Lorenzini to detect electric field pulses that last only a few thousandths of a second. On the contrary, these organs are tuned to sense only the slowest-changing electric fields, such as those generated by electrochemical batteries.

This detection ability would make sense because all biological cells in the body function as batteries as a consequence of their structure. A typical battery produces a voltage when two salt solutions with different net electric charges are separated inside an electrochemical cell. Opposite charges attract, and the resulting movement of charge creates an electric current. Likewise, living cells contain a salt solution that differs from seawater, causing a voltage to arise at the interface. Consequently, a fish's body in seawater operates as a weak battery that emits an electric field around it. The field produced by this battery changes slowly as the fish pumps water through its gills.

By using an electronic amplifier in the 1970s biologist Adrianus Kalmijn, then at the University of Utrecht in the Netherlands (and now at the Scripps Institution of Oceanography), showed that animals produced bioelectric fields in seawater. These very weak fields changed little (or not at all) over time, exactly the type of electric signature ampullae of Lorenzini are equipped to detect. Kalmijn also demonstrated that a captive shark would locate and attack electrodes he had buried in the sand of an aquarium if the elec-

FRED BAVENDAM *Minden Pictures (ray)*; NORBERT WU *Minden Pictures (sawfish)*; STEPHEN FRINK *Corbis (electric ray)*; WIL MEINDERTS *Foto Natura/Minden Pictures (sturgeon)*; JEAN-PAUL FERRERO *Auscape/Minden Pictures (lungfish)*

[EXPERIMENTS]

INVESTIGATING AN ANCIENT SENSE

RATFISH, or chimaera, senses the surrounding water with electroreceptors, a fact that the author proved using a ring-shaped aquarium (*diagram*).

Sharks were not the first fish to possess electroreceptors; their now extinct ancestors sensed electric fields in ancient seas. My own early research on electroreception focused on whether a peculiar fish that also evolved from these long-lost species—the primitive, deep-ocean dweller called chimaera—has electroreception.

I first encountered one of these bizarre-looking creatures in the late 1970s on a commercial fishing trawler when I was a graduate student at Moss Landing Marine Labs in California. The chimaera had large incisors that prevented its mouth from fully closing. This feature and its big eyes made it resemble a bunny or a rat—which is why it is commonly called a rabbitfish or ratfish.

Because the ratfish had no commercial value, the captain allowed me to take it home for study. I soon noted that the bulk of the head between the skin and underlying muscle was filled with a transparent gelatinous mass. When I shone a light through the jelly at an angle, I saw a tangle of transparent, gel-filled tubes that radiated out to pores on the surface of the head, which resembled ampullae of Lorenzini in sharks. I suspected that ratfish also possess these organs, but to confirm this conjecture, I needed to catch a ratfish unharmed and keep it alive long enough for experimentation.

To this end, I enlisted the help of the crews of the commercial fishing boats that ply the seas around Monterey Bay. One foggy morning the *Holiday II* brought in a live ratfish, and the skipper radioed me to pick it up at the dock. Back at my lab, I placed the fish in a ring-shaped aquarium in which seawater circulated constantly (*diagram*). The center of the ring was just large enough to allow me to observe the fish as it swam against the water current (its preferred direction).

I soon realized that the ratfish's tendency to swim against the flow might help to answer my questions. First, I buried electrodes under the sand. When the ratfish swam over the hidden electrodes, I switched on the electric field and simultaneously gently tapped the fish with a glass rod, coaxing it to swim with the water current. The ratfish soon reversed course, returning to its favored route. I assumed that if the fish could detect the weak electric field, it would come to associate the field with the annoying glass rod. If that occurred, the ratfish might learn to turn around on its own when I flipped the switch only. If the animal never learned to do this, the failure would mean either that it could not sense weak electric fields or that it was untrainable.

After considerable effort, I finally got the result I sought. I hit the switch, and the chimaera reversed direction instantly. It had sensed the electric field and figured out the routine. From then on, every time I applied the electric stimulus, the ratfish turned around, but it passed over the electrodes without hesitation if I did not engage the field. By adjusting the field's intensity and frequency, I found that the fish easily detected fields as weak as those emitted by fish in seawater.

Although the experiment showed that ratfish can detect weak electric fields, it did not prove that the fish use the structures resembling ampullae of Lorenzini for that purpose. Electrophysiologist David Lange of the Scripps Institution of Oceanography and I set out to address this issue with the same ratfish. Taking the approach employed by Alexander Sand in 1938, we recorded the activity of the nerves connected to these organs. When a nerve impulse raced from the mystery organ to the brain, a green phosphorescent wave trace swept across our oscilloscope screen and a loud crack resounded from a speaker.

As the fish slept peacefully under anesthesia, the nerve firing pulsed gently in rhythm with its respiration. When we placed an electric field near the opening of one of the skin pores, though, the laboratory instantly filled with noisy cracks, reflecting a stream of nerve impulses shooting to its brain. Next, we pulsed the electric field, and the impulses followed in lockstep, like Marines on the march. And when we reversed the field's polarity, we demonstrated that the negative pole excited the organ, whereas the positive pole inhibited its function, just as R. W. Murray observed with the ampullae in sharks. There was no doubt that the chimaera had electroreceptors. Later examination revealed that the ratfish's electrosensors are identical to those in sharks. —***R.D.F.***

NORBERT WU *Minden Pictures (ratfish)*; MELISSA THOMAS *(diagram)*

MAGNETIC REPELLENTS?

Inventors are attempting to drive sharks away from fish baits and maybe even swimmers by zapping their sensitive electroreceptors with strong magnets. The idea is to confuse a shark's electrosensors by inducing an internal voltage as its body passes through the magnet's field, say researchers and entrepreneurs Samuel Gruber, Eric Stroud and Mike Herrmann.

"The focus is on saving sharks, not humans," explains Gruber, a marine biologist at the University of Miami. The World Wildlife Fund estimates that 20 percent of shark species are endangered. If fixed to commercial longlines, such devices might save 50,000 sharks a night from being caught by fishers worldwide, Gruber claims.

With support from the World Wildlife Fund, the team is developing a baited fishhook with a powerful magnet (*black cylinder, above*) attached to the leader. Commercial and game fish, which do not have electroreceptors, would bite the hook unawares. Preliminary tests are encouraging, but don't swim in the ocean with suits stuffed with magnets just yet; no peer-reviewed scientific studies have shown if magnets have any effect whatsoever on shark behavior. ***—R.D.F.***

trodes emitted fields mimicking those produced by the shark's typical prey. (My own early work in electroreception paralleled Kalmijn's research, except that I focused on a relative of sharks called chimaera [*see box on preceding page*].)

Electroreception in the Wild

Showing that fish with ampullae of Lorenzini respond to electric fields in the controlled conditions of the laboratory is one thing, but determining if and how they use this sense in their own environment is another. This task proved challenging in part because weak electrical signals from prey can be accompanied by electrical noise generated by other natural phenomena—salinity, temperature, water motion, acidity, and so on. In the ocean, even a metal wire creates a voltage that any shark can easily perceive.

To test how fish use this sensory ability in nature, such as while hunting, we had to observe them doing so in the sea—which is how we ended up on the small fiberglass (nonmetallic) boat with the square hole cut into its deck. In 1981, hoping to see if large oceangoing sharks relied on electroreception during normal feeding, Melanie and I, as well as Kalmijn and his associate Gail Heyer of the Woods Hole Oceanographic Institution, developed a T-shaped apparatus with sets of electrodes positioned at each end.

Later that summer, out at sea, we lowered the device through the cutout in the deck and pumped ground-up fish into the water through a port located at the join between the electrodes. We then energized the electrodes to produce electric fields mimicking those emitted by sharks' typical prey fish. One person activated one electrode at a time in a random sequence while a second person (who did not know which electrode was activated in any instant) observed the effect on the sharks. If the animals preferentially attacked the activated electrode, we would know they used their electric sense to catch prey.

Crouching on the boat deck during the first night of our experiment, we peered into the hole as a great blue shark circled and then zeroed in on the scent of ground fish flowing from the apparatus. It swam straight toward the odor and at the last instant veered sharply to the right, snapping the right leg of the T in its jaws. The shark shuddered and thrashed and abruptly released the apparatus. In the final moment of the attack the predator had ignored the odor source and instead turned to bite the activated electrode. Throughout the summer we witnessed many attacks in which the animals strongly preferred the activated electrode over the inactive electrode and the source of food odor.

The finding that electroreception can override even the strong sensory cues of taste and smell in the final moments of attack might explain puzzling anecdotal accounts of shark attacks on humans. People have reported instances in which a human victim of a shark attack was repeatedly assaulted while being towed to safety by another swimmer whom the shark ignored during the rescue. Although a shark might be expected to lose track of its initial victim when blood obscured vision and smell, it seems that its electroreception sense enables it to locate the strong electric field originating from the bloody salts pouring from the wounds of the victim.

Sharks use all their senses when they hunt, but each one has special advantages and different sensitivities [*see box on opposite page*]. Smell and hearing would be most useful for locating prey from great distances. Vision, lateral line senses and taste would become more important at closer ranges. During the terminal phase of an attack, when a shark comes within a meter of its prey, however, electroreception becomes the most useful way to precisely locate the prey and correctly orient its jaws. Such an insight may one day inform the development of a device that could decoy sharks away from swimmers.

My colleagues and I have focused on feeding behavior because it is relatively easy to elicit in sharks, but these fish undoubtedly wield their electric sense for other purposes as well. We can only imagine what it must be like to see the world through this strange and altogether unfamiliar sense. ■

[THE AUTHOR]

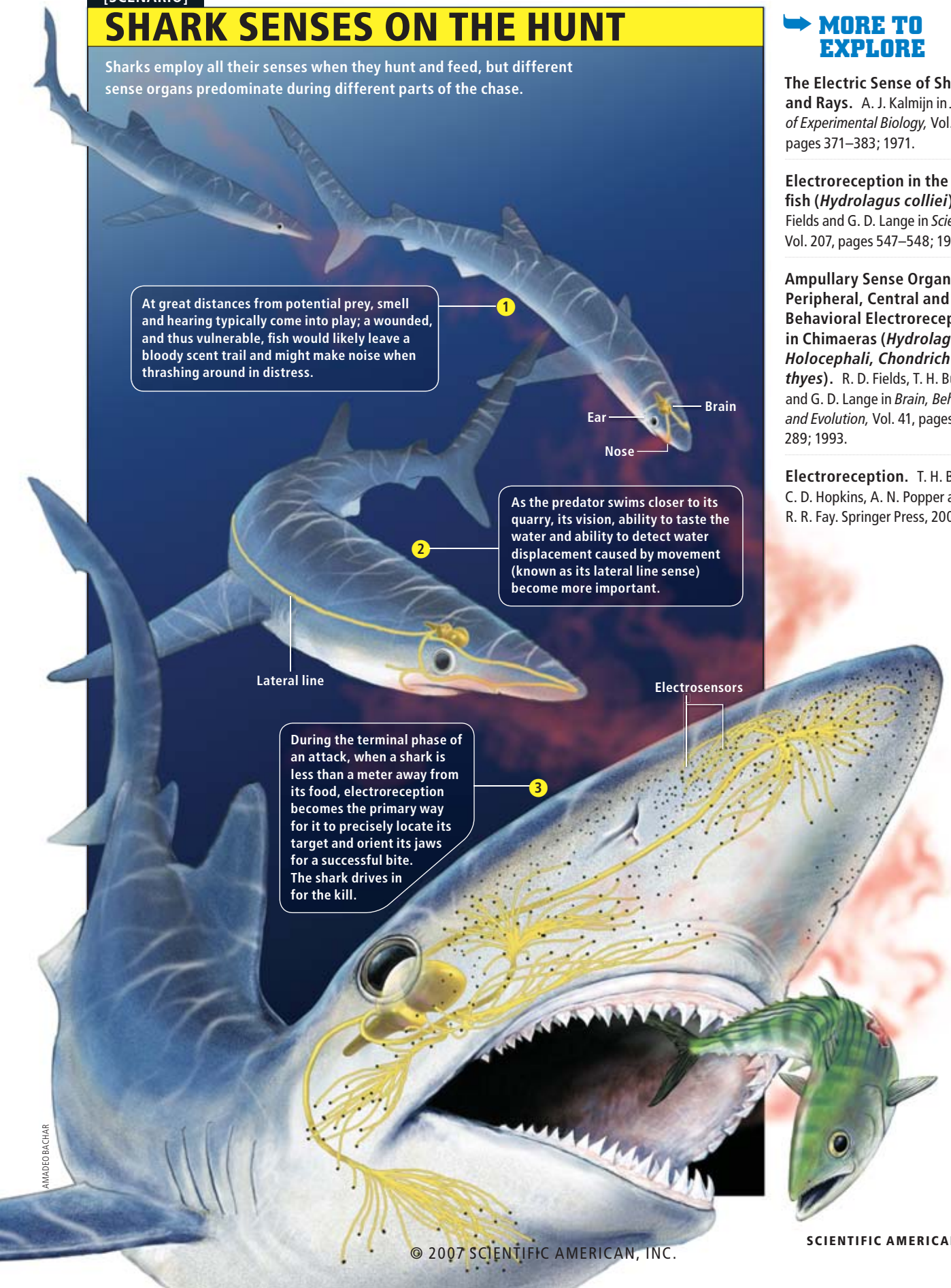
R. Douglas Fields, who holds an M.A. from Moss Landing Marine Labs in California and a Ph.D. in biological oceanography from the Scripps Institution of Oceanography, is a neurobiologist at the National Institutes of Health. For his shark studies, he collaborates with his wife, Melanie Fields, a high school biology teacher. Outside of work, Fields spends time rock climbing, scuba diving and guitar making. This is his third article for *Scientific American.*

ERIC STROUD AND MICHAEL HERMANN *Shark Defense (top);* COURTESY OF R. DOUGLAS FIELDS *(bottom)*

[SCENARIO]

SHARK SENSES ON THE HUNT

Sharks employ all their senses when they hunt and feed, but different sense organs predominate during different parts of the chase.



AMADEO BACHAR

MORE TO EXPLORE

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Ampullary Sense Organs, Peripheral, Central and Behavioral Electroreception in Chimaeras (*Hydrolagus, Holocephali, Chondrichthyes*). R. D. Fields, T. H. Bullock and G. D. Lange in *Brain, Behavior and Evolution,* Vol. 41, pages 269–289; 1993.

Electroreception. T. H. Bullock, C. D. Hopkins, A. N. Popper and R. R. Fay. Springer Press, 2005.

MODERN FOOD CROPS depend heavily on irrigation and other human inputs while depleting the land and polluting surrounding environments. Development of perennial versions, such as the experimental hybrid of intermediate wheatgrass and triticale shown on the opposite page, could reduce those burdens.

Future Farming: A Return to Roots?

Large-scale agriculture would become more sustainable if major crop plants lived for years and built deep root systems

By Jerry D. Glover, Cindy M. Cox and John P. Reganold

For many of us in affluent regions, our bathroom scales indicate that we get more than enough to eat, which may lead some to believe that it is easy, perhaps too easy, for farmers to grow our food. On the contrary, modern agriculture requires vast areas of land, along with regular infusions of water, energy and chemicals. Noting these resource demands, the 2005 United Nations–sponsored Millennium Ecosystem Assessment suggested that agriculture may be the "largest threat to biodiversity and ecosystem function of any single human activity."

Today most of humanity's food comes directly or indirectly (as animal feed) from cereal grains, legumes and oilseed crops. These staples are appealing to producers and consumers because they are easy to transport and store, relatively imperishable, and fairly high in protein and calories. As a result, such crops occupy about 80 percent of global agricultural land. But they are all annual plants, meaning that they must be grown anew from seeds every year, typically using resource-intensive cultivation methods. More troubling, the environmental degradation caused by agriculture will likely worsen as the hungry human population grows to eight billion or 10 billion in the coming decades.

That is why a number of plant breeders, agronomists and ecologists are working to develop grain-cropping systems that will function much more like the natural ecosystems displaced by agriculture. The key to our collective success is transforming the major grain crops into perennials, which can live for many years. The idea, actually decades old, may take decades more to realize, but significant advances in plant-breeding science are bringing this goal within sight at last.

Roots of the Problem

Most of the farmers, inventors and scientists who have walked farm fields imagining how to overcome difficulties in cultivation probably saw agriculture through the lens of its contemporary successes and failures. But in the 1970s Kansas plant geneticist Wes Jackson took a 10,000-year step into the past to compare agriculture with the natural systems that preceded it. Before humans boosted the abundance of annuals through domestication and farming, mixtures of perennial plants dominated nearly all the planet's landscapes—as they still do in uncultivated areas today. More than 85 percent of North America's native plant species, for example, are perennials.

Jackson observed that the perennial grasses and flowers of Kansas's tall-grass prairies were highly productive year after year, even as they built and maintained rich soils. They needed no fertilizers, pesticides or herbicides to thrive while fending off pests and disease. Water running off or through the prairie soils was clear, and wildlife was abundant.

In contrast, Jackson saw that nearby fields of annual crops, such as maize, sorghum, wheat, sunflowers and soybeans, required frequent and expensive care to remain productive. Because annuals have relatively shallow roots—most of which occur in the top 0.3 meter of soil—and live only until harvest, many farmed areas had problems with soil erosion, depletion of soil fertility or water contamination. Moreover, the eerily quiet farm fields were mostly barren of wildlife. In short, sustaining annual monocultures in so many places *was* the problem, and the solution lay beneath Jackson's boots: hardy and diverse perennial root systems.

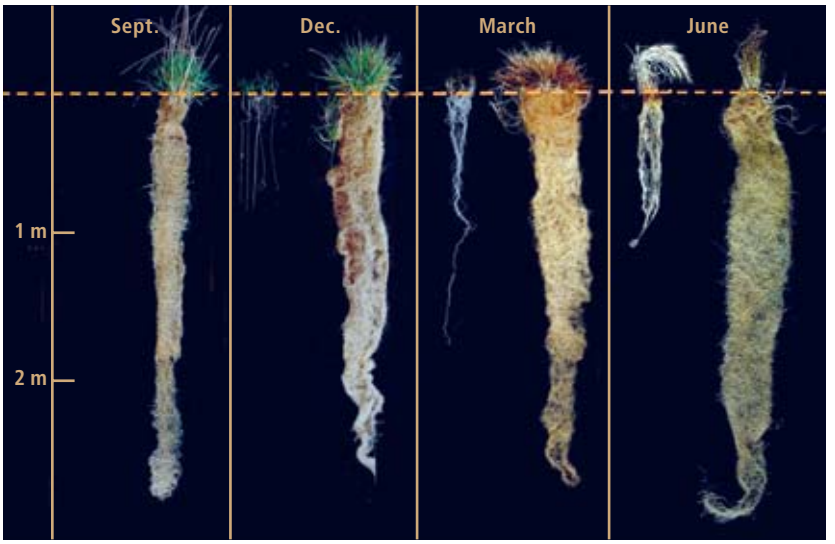
If annual crops are problematic and natural

KEY FACTS

- Modern agriculture's intensive land use quashes natural biodiversity and ecosystems. Meanwhile the population will balloon to between eight billion and 10 billion in the coming decades, requiring that more acres be cultivated.
- Replacing single-season crops with perennials would create large root systems capable of preserving the soil and would allow cultivation in areas currently considered marginal.
- The challenge is monumental, but if plant scientists succeed, the achievement would rival humanity's original domestication of food crops over the past 10 millennia—and be just as revolutionary.

—The Editors

MICHAEL S. LEWIS *National Geographic/Getty Images (opposite page)*; JIM RICHARDSON *(this page)*



PERENNIAL PLANTS, such as intermediate wheatgrass (*at right in panels above*), access nutrients and water in larger volumes of soil with their well-developed roots than do annuals, such as winter wheat (*at left in panels above*). In turn, perennial roots support microorganisms and other biological activity that enrich soil. The resulting dark, granular soil (*far right*), taken from underneath a perennial meadow, retains ample water and nutrients. Soil from an adjacent annual field (*near right*) is lighter with a weak, clumped structure.

ecosystems offer advantages, why do none of our important grain crops have perennial roots? The answer lies in the origins of farming. When our Neolithic ancestors started harvesting seed-bearing plants near their settlements, several factors probably determined why they favored annuals.

The earliest annuals to be domesticated, emmer wheat and wild barley, did have appealingly large seeds. And to ensure a reliable harvest every year, the first farmers would have replanted some of the seeds they collected. The characteristics of wild plants can vary greatly, however, so the seeds of plants with the most desirable traits, such as high yield, easy threshing and resistance to shattering, would have been favored. Thus, active cultivation and the unwitting application of evolutionary selection pressure quickly resulted in domesticated annual plants with more appealing qualities than their wild annual relatives. Although some perennial plants might also have had good-size seeds, they did not need to be replanted and so would not have been subjected to—or benefited from—the same selection process.

Roots as Solution

Today the traits of perennials are also becoming better appreciated. With their roots commonly exceeding depths of two meters, perennial plant communities are critical regulators of ecosystem functions, such as water management and carbon and nitrogen cycling. Although they do have to invest energy in maintaining enough underground tissue to survive the winter, perennial roots spring into action deep within the soil whenever temperatures are warm enough and nutrients and water are available. Their constant state of preparedness allows them to be highly productive yet resilient in the face of environmental stresses.

In a century-long study of factors affecting soil erosion, timothy grass, a perennial hay crop, proved roughly 54 times more effective in maintaining topsoil than annual crops did. Scientists have also documented a fivefold reduction in water loss and a 35-fold reduction in nitrate loss from soil planted with alfalfa and mixed perennial grasses as compared with soil under corn and soybeans. Greater root depths and longer growing seasons also let perennials boost their sequestration of carbon, the main ingredient of soil organic matter, by 50 percent or more as compared with annually cropped fields. Because they do not need to be replanted every year, perennials require fewer passes of farm machinery and fewer inputs of pesticides and fertilizers as well, which reduces fossil-fuel use. The plants thus lower the amount of carbon dioxide in the air while improving the soil's fertility.

Herbicide costs for annual crop production may be four to 8.5 times the herbicide costs for perennial crop production, so fewer inputs in perennial systems mean lower cash expenditures for the farmer. Wildlife also benefits: bird populations, for instance, have been shown to be seven times more dense in perennial crop fields than in annual crop fields. Perhaps most important for a hungry world, perennials are far more capable of sustainable cultivation on marginal lands, which already have poor soil quality or which would be quickly depleted by a few years of intensive annual cropping.

For all these reasons, plant breeders in the U.S. and elsewhere have initiated research and breeding programs over the past five years to develop wheat, sorghum, sunflower, intermediate wheatgrass and other species as perennial grain crops. When compared with research devoted to annual crops, perennial grain development is still in the toddler stage. Taking advantage of

JERRY D. GLOVER (*roots*); STEVE CULMAN *Cornell University* (*soils*); GETTY IMAGES (*wheat stalks*)

the significant advances in plant breeding over the past two or three decades, however, will make the large-scale development of high-yield perennial grain crops feasible within the next 25 to 50 years.

Perennial crop developers are employing essentially the same two methods as those used by many other agricultural scientists: direct domestication of wild plants and hybridization of existing annual crop plants with their wild relatives. These techniques are potentially complementary, but each presents a distinct set of challenges and advantages as well.

Assisted Evolution

Direct domestication of wild perennials is the more straightforward approach to creating perennial crops. Relying on time-tested methods of observation and selection of superior individual plants, breeders seek to increase the frequency of genes for desirable traits, such as easy separation of seed from husk, a nonshattering seed, large seed size, synchronous maturity, palatability, strong stems, and high seed yield. Many existing crops, such as corn and sunflowers, lent themselves readily to domestication in this manner. Native Americans, for example, turned wild sunflowers with small heads and seeds into the familiar large-headed and large-seeded sunflower [*see box on page 88*].

Active perennial grain domestication programs are currently focused on intermediate wheatgrass (*Thinopyrum intermedium*), Maximilian sunflower (*Helianthus maximiliani*), Illinois bundleflower (*Desmanthus illinoensis*) and flax (a perennial species of the *Linum* genus). Of these, the domestication of intermediate wheatgrass, a perennial relative of wheat, is perhaps in the most advanced stages.

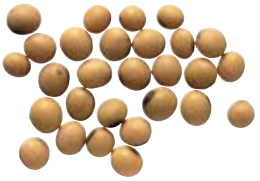
To use an existing annual crop plant in creating a perennial, wide hybridization—a forced mating of two different plant species—can bring together the best qualities of the domesticated annual and its wild perennial relative. Domesticated crops already possess desirable attributes, such as high yield, whereas their wild relatives can contribute genetic variations for traits such as the perennial habit itself as well as resistance to pests and disease.

Of the 13 most widely grown grain and oilseed crops, 10 are capable of hybridization with perennial relatives, according to plant breeder T. Stan Cox of the Land Institute, a Kansas nonprofit that Jackson co-founded to pursue sustainable agriculture. A handful of breeding programs across the U.S. are currently pursuing such interspecific (between species) and intergeneric (between genera) hybrids to develop perennial wheat, sorghum, corn, flax and oilseed sunflower. For more than a decade, University of Manitoba researchers have studied resource use in perennial systems, and now a number of Canadian institutions have started on the long road to developing perennial grain programs as well. The University of Western Australia has already established a perennial wheat program as part of that country's Cooperative Research Center for Future Farm Industries. In addition, scientists at the Food Crops Research Institute in Kunming, China, are continuing work initiated by the International Rice Research Institute in the 1990s to develop perennial upland rice hybrids.

At the Land Institute, breeders are working both on domesticating perennial wheatgrass and on crossing assorted perennial wheatgrass species (in particular, *Th. intermedium*, *Th. ponticum* and *Th. elongatum*) with annual wheats. At present, 1,500 such hybrids and thousands of their progeny are being screened for perennial traits. The process of creating these hybrids is itself labor-intensive and time-consuming. Once breeders identify candidates for hybridization, they must manage gene exchanges between disparate species by manipulating pollen to make a large number of crosses between plants, selecting the progeny with desirable traits, and repeating this cycle of crossing and selection again and again.

Hybridization nonetheless is a potentially faster means to create a perennial crop plant than domestication, although more technology is often required to overcome genetic incompatibilities between the parent plants. A seed produced by crossing two distantly related species, for example, will often abort before it is fully developed. Such a specimen can be "rescued" as an embryo by growing it on artificial medium until it produces a few roots and leaves, then transferring the seedling to soil, where it can grow like any other plant. When it reaches the reproductive stage, however, the hybrid's genetic anomalies frequently manifest as an inability to produce seed.

A partially or fully sterile hybrid generally results from incompatible parental chromosomes within its cells. To produce eggs or pollen, the hybrid's chromosomes must line up during meiosis (the process by which sex cells halve their chromosomes in preparation for joining with



TOP 10 CROPS

Annual cereal grains, food legumes and oilseed plants claimed 80 percent of global harvested cropland in 2004. The top three grains covered more than half that area.

CROP	LAND %
1. Wheat	17.8
2. Rice	12.5
3. Maize	12.2
4. Soybeans	7.6
5. Barley	4.7
6. Sorghum	3.5
7. Cottonseed	2.9
8. Dry beans	2.9
9. Millet	2.8
10. Rapeseed/mustard	2.2

[THE AUTHORS]

Jerry D. Glover is an agroecologist and director of graduate research at the Land Institute in Salina, Kan., a nonprofit organization devoted to education and research in sustainable agriculture. Cindy M. Cox is a plant pathologist and geneticist in the institute's plant-breeding program. John P. Reganold, who is Regents Professor of Soil Science at Washington State University at Pullman, specializes in sustainable agriculture and last wrote for *Scientific American* on that subject in the June 1990 issue.

GETTY IMAGES (*soybeans*); SOURCE: FAOSTAT

Experimental perennial wheat

[BENEFITS]

SUSTAINABLE FARMING: NEW VS. NOW

The potential advantages of future perennial crop plants are visible today by comparing perennial wheatgrass (*below left*) growing alongside domesticated annual wheat (*below right*). Although a perennial wheat could one day yield grains similar to those of the annual crop, it might live for many years and look much more like its wheatgrass relative belowground. Perennial crops would transform the process of farming and its environmental effects by using resources more effectively, thereby being less dependent on human inputs and more productive for a longer time. Perennials also anchor and support the ecosystem that nourishes them, whereas short-lived and short-rooted annuals allow water, soil and nutrients to be lost.

CARBON FACTOR

Global warming potential—greenhouse gases released into the atmosphere by crop production inputs, minus carbon sequestered in soil—is negative for perennial crops. The more resilient perennials are also expected to fare better than annuals in a warming climate.

SOIL CARBON SEQUESTERED
(kilograms per hectare per year)

Annual crops	0 to 450
Perennial crops	320 to 1,100

GLOBAL WARMING POTENTIAL
(kilograms of CO_2 equivalent per hectare per year)

Annual crops	140 to 1,140
Perennial crops	–1,050 to –200

ESTIMATED IMPACT ON YIELD OF 3° C TO 8° C TEMPERATURE INCREASE
(megagrams per hectare)

Annual crops	–1.5 to –0.5
Perennial crops	+5

JIM RICHARDSON (*soil cross section*); THE LAND INSTITUTE (*insets on opposite page*); JIM RICHARDSON (*farm machinery*); SeaWiFS PROJECT (*NASA/GSFC*) AND GeoEye (*dead zone*); KEN CEDENO (*tilled land*); JACK DYKINGA *USDA/ARS* (*erosion*)

another gamete) and exchange genetic information with one another. If the chromosomes cannot find counterparts because each parent's version is too different, or if they differ in number, the meiosis line dance is disrupted. This problem can be overcome in a few ways. Because sterile hybrids are usually unable to produce male gametes but are partially fertile with female gametes, pollinating them with one of the original parents, known as backcrossing, can restore fertility. Doubling the number of chromosomes, either spontaneously or by adding chemicals such as colchicine, is another strategy. Although each method allows for chromosome pairing, subsequent chromosome eliminations in each successive generation often happen in perennial wheat hybrids, particularly to chromosomes inherited from the perennial parent.

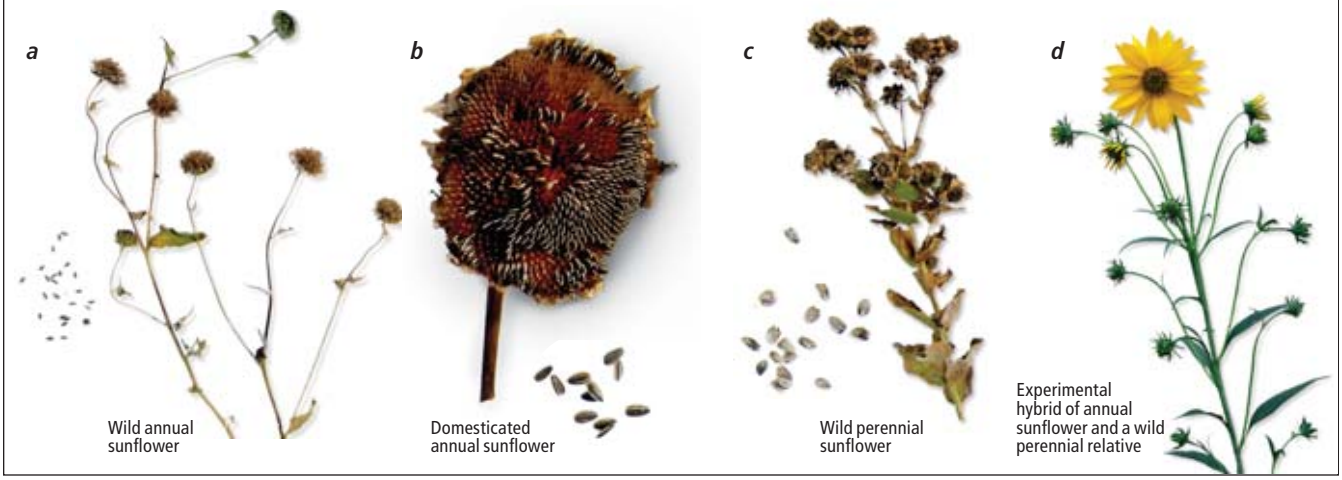
Because of the challenging gene pools created by wide hybridization, when fertile perennial hybrids are identified, biotechnology techniques that can reveal which parent contributed parts of the progeny's genome are useful. One of these, genomic in situ hybridization, for example, distinguishes the perennial parent's chromosomes from those of the annual parent by color fluorescence and also detects chromosome anomalies, such as structural rearrangements between unrelated chromosomes [*see bottom illustration on next page*]. Such analytical tools can help speed up a breeding program once breeders discover desirable and undesirable chromosome combinations, without compromising the potential for using perennial grains in organic agriculture, where genetically engineered crops are not allowed.

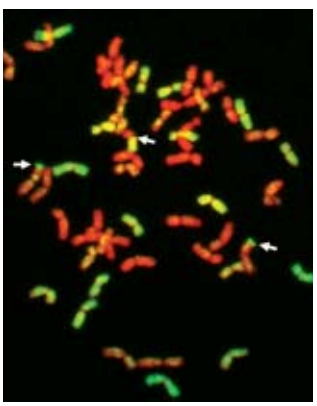
Another valuable method for speeding and improving traditional plant breeding is known as marker-assisted selection. DNA sequences associated with specific traits serve as markers that allow breeders to screen crosses as seedlings for desired attributes without having to wait until the plants grow to maturity [see "Back to the Future of Cereals," by Stephen A. Goff and John M. Salmeron; Scientific American, August 2004]. At present, no markers specific to perennial plant breeding have been established, although it is only a matter of time. Scientists at Washington State University, for example, have already determined that chromosome 4E in *Th. elongatum* wheatgrass is necessary for the important perennial trait of regrowth following a sexual reproduction cycle. Narrowing down

[THE NEXT STEP]

CREATING A NEW CROP

To develop high-yield perennial crop plants, scientists and breeders can either domesticate a wild perennial plant to improve its traits or hybridize an annual crop plant with a wild perennial relative to blend their best qualities. Each method requires time- and labor-intensive plant crossbreeding and analysis. Native Americans spent thousands of years domesticating the small-seeded wild annual sunflower (*a*) into the modern annual crop plant (*b*) by selecting and cultivating plants with desirable traits, such as large seeds and yields. Efforts are currently under way to directly domesticate wild perennial sunflower species (*c*) and also to produce hybrids of the modern annual and wild perennials (*d*).





CHROMOSOMES of an experimental hybrid perennial wheat plant are tagged with fluorescence to reveal whether they originated with the hybrid's wheatgrass (*green*) or wheat (*red*) parent. This technique helps to identify desirable chromosome combinations and highlights anomalies, such as fused chromosomes (*arrows*).

the region on 4E to the gene or genes that produce the trait would reveal relevant DNA markers that will save breeders a year of growing time in assessing hybrids.

Perennialism is nonetheless an intricate life path that goes well beyond a single trait, let alone a single gene. Because of this complexity, transgenic modification (insertion of foreign DNA) is unlikely to be useful in developing perennial grains, at least initially. Down the road, transgenic technology may have a role in refining simple inherited traits. For example, if a domesticated perennial wheatgrass is successfully developed but still lacks the right combination of gluten-protein genes necessary for making good-quality bread, gluten genes from annual wheat could be inserted into the perennial plant.

Trade-offs and Payoffs

Although perennial crops, such as alfalfa and sugarcane, already exist around the world, none has seed yields comparable to those of annual grain crops. At first glance, the idea that plants can simultaneously direct resources to building and maintaining perennial root systems and also produce ample yields of edible grains may seem counterintuitive. Carbon, which is captured through photosynthesis, is the plant's main building block and must be allocated among its various parts.

Critics of the idea that perennials could have high seed yield often focus on such physiological trade-offs, assuming that the amount of carbon available to a plant is fixed and therefore that carbon allocated to seeds always comes at the expense of perennating structures, such as roots and rhizomes. Doubters also often overlook the fact that the life spans of perennial plants exist along a spectrum. Some perennial prairie plants may persist for 50 to 100 years, whereas others live for only a few years. Fortunately for breeders, plants are relatively flexible organisms: responsive to selection pressures, they are able to change the size of their total carbon "pies" depending on environmental conditions and to change the allocation of pie slices.

A hypothetical wild perennial species might live 20 years in its highly competitive natural environment and produce only small amounts of seed in any year. Its carbon pie is small, with much of it going toward fending off pests and disease, competing for a few resources and persisting in variable conditions. When breeders take the wild specimen out of its resource-strapped natural setting and place it into a managed environment, its total carbon pie suddenly grows, resulting in a bigger plant.

Over time, breeders can also change the size of the carbon slices within that larger pie. Modern Green Revolution grain breeding, when combined with increased use of fertilizers, more than doubled the yield of many annual grain

THE LAND INSTITUTE (*sunflowers*); CINDY M. COX (*chromosomes*)

crops, and those increases were achieved in plants that did not have perennating structures to sacrifice. Breeders attained a portion of those impressive yield expansions in annual crops by selecting for plants that produced less stem and leaf mass, thereby reallocating that carbon to seed production.

Yields can be similarly increased without eliminating the organs and structures required for overwintering in perennial grain crops. In fact, many perennials, which are larger overall than annuals, offer more potential for breeders to reallocate vegetative growth to seed production. Furthermore, for a perennial grain crop to be successful in meeting human needs, it might need to live for only five or 10 years.

In other words, the wild perennial is unnecessarily "overbuilt" for a managed agricultural setting. Much of the carbon allocated to the plant's survival mechanisms, such as those allowing it to survive infrequent droughts, could be reallocated to seed production.

Greener Farms

Thus, we can begin to imagine a day 50 years from now when farmers around the world are walking through their fields of perennial grain crops. These plots would function much like the Kansas prairies walked by Wes Jackson, while also producing food. Belowground, different types of perennial roots—some resembling the long taproots of alfalfa and others more like the thick, fibrous tangle of wheatgrass roots—would coexist, making use of different soil layers. Crops with alternative seasonal growth habits could be cultivated together to extend the overall growing season. Fewer inputs and greater biodiversity would in turn benefit the environment and the farmer's bottom line.

Global conditions—agricultural, ecological, economic and political—are changing rapidly in ways that could promote efforts to create perennial crops. For instance, as pressure mounts on the U.S. and Europe to cut or eliminate farm subsidies, which primarily support annual cropping systems, more funds could be made available for perennials research. And as energy prices soar and the costs of environmental degradation are increasingly appreciated, budgeting public money for long-term projects that will reduce resource consumption and land depletion will become more politically popular.

Because the long timeline for release of perennial grain crops discourages private-sector investment at this point, large-scale government or philanthropic funding is needed to build up a critical mass of scientists and research programs. Although commercial companies may not profit as much by selling fertilizers and pesticides to farmers producing perennial grains, they, too, will most likely adapt to these new crops with new products and services.

Annual grain production will undoubtedly still be important 50 years from now—some crops, such as soybeans, will probably be difficult to perennialize, and perennials will not completely eliminate problems such as disease, weeds and soil fertility losses. Deep roots, however, mean resilience. Establishing the roots of agriculture based on perennial crops now will give future farmers more choices in what they can grow and where, while sustainably producing food for the burgeoning world population that is depending on them. ■

BREEDING HYBRID plants can require rescuing an embryo from the ovary (*left*). A researcher bags annual sorghum heads to collect pollen, with tall perennial sorghum in the background (*right*).

MORE TO EXPLORE

Perennial Grain Crops: An Agricultural Revolution. Edited by Jerry D. Glover and William Wilhelm. Special issue of *Renewable Agriculture and Food Systems,* Vol. 20, No. 1; March 2005.

Wes Jackson (35 Who Made a Difference). Craig Canine in special anniversary issue of *Smithsonian,* Vol. 36, No. 8, pages 81–82; November 2005.

Prospects for Developing Perennial Grain Crops. Thomas S. Cox, Jerry D. Glover, David L. Van Tassel, Cindy M. Cox and Lee D. DeHaan in *BioScience,* Vol. 56, No. 8, pages 649–659; August 2006.

Sustainable Development of the Agricultural Bio-Economy. Nicholas Jordan et al. in *Science,* Vol. 316, pages 1570–1571; June 15, 2007.

The Land Institute: www.landinstitute.org

THE LAND INSTITUTE (*above left*); JIM RICHARDSON (*above right*); GETTY IMAGES (*below right*)

Data Center in a BOX

A shipping container stuffed with servers could usher in the era of cloud computing *By M. Mitchell Waldrop*

KEY CONCEPTS

- Massive computing power can now be delivered to anyone's doorstep inside a standard 20-foot shipping container.
- The box provides up to 250 servers boasting seven terabytes of active memory and two petabytes of storage—enough resources to support 10,000 desktop users.
- Sun Microsystems says its turnkey system can be operational for one-hundredth the cost of building a traditional data center.
- The beefy boxes could also quickly expand the Internet's computing and storage capacity, ushering in so-called cloud computing, where individuals rely on nimble personal devices that are unencumbered with basic software and instead use programs that reside on the Net.

—The Editors

The next steel shipping container you see being hauled by a truck or train might not stow the usual mass of lumber, textiles or foodstuffs. It might hold 10 tons of finely interlaced computer servers, ready to be deposited in a parking lot to serve 10,000 employees at a corporate headquarters—or 10,000 people on the Internet. Sun Microsystems has just started delivering these data-centers-to-go, taking the concept of portable computing to a whole new level.

True, the Project Blackbox system is portable only in the industrial sense that it is integrated into a standard 20-foot shipping container. But once delivered to a site, it is almost as self-contained as any laptop. All the system requires is a power cable and an Internet connection—plus a water supply and an external chiller for cooling. As many as 250 servers inside provide up to seven terabytes of active memory and more than two petabytes of disk storage. Perhaps most critically, says Greg Papadopoulos, Sun's chief technology officer in Menlo Park, Calif., Project Blackbox will deliver that functionality in about one-tenth the time and at one-hundredth the cost of building a traditional computer room of equal prowess.

That prospect means such boxed data centers could not only replace the corporate data center, they could also transform the computer experience for all of us. "Project Blackbox symbolizes a big bet we're making as a company," Papadopoulos explains. "It's a bet that the billions and billions of client machines we'll have in the future—desktops, handhelds, iPods, whatever—will spend most of their time interacting with the network." These devices will have little need to store and run common software applications the way most computers do today. Instead they will simply access programs online that enable word processing, spreadsheets, and so on.

This transition is already well on its way, under names such as grid, utility or cloud computing. More and more people use Internet services for e-mail (such as Hotmail), blogging (Blogger), social networking (MySpace), mapping (Google Earth) and other tasks. They do not host the software on their own machines; they just link to it when they need it. Papadopoulos compares the movement to what happened with electricity a century ago: very few of us keep a generator in the basement anymore; we just plug into the power grid and consume electricity as needed.

PARKING GARAGE could be the low-cost site for a company's new data center—if an Ethernet link and a water supply were available.

SUN MICROSYSTEMS

Powering the Cloud

If cloud computing is the future, the Net will have to get a lot bigger, fast, and Project Blackbox could play a crucial role. Of course, Papadopoulos says, the Internet already has many computational power plants, in the form of big, institutional data centers crammed with hundreds of computers in floor-to-ceiling racks.

The problem is that the generating capacity of these plants is slipping further and further behind the growth in demand. Each new data center has to be custom-designed and specially installed, computer by computer, in a process that can take years and cost tens of millions of dollars. Once up and running, the centers cost a fortune to operate, both because the computer rooms tend to be carved out of high-rent office space and because they require massive air-conditioning around the clock to cool the sea of power-hungry microprocessors. As Jonathan Schwartz, Sun's chief executive officer, put it at the Project Blackbox debut ceremony, "Just about every chief information officer and start-up I meet says they're crippled by data-center energy and space constraints."

Sun's goal is to offer a way out. The big companies such as Qwest, Level 3, Akamai and Google that erect the huge server farms that support the Internet's ever skyrocketing traffic could add capacity much faster by linking together the prefab containers, saving millions of dollars in the process. They and other firms could also sprinkle Blackboxes around in numerous other places to create nodes in the expanding grid.

At the same time, companies that must expand in-house computing would have new options. A firm in New York City, say, could augment its downtown data center with containers on a rooftop or in a parking garage—or in a low-rent warehouse in New Jersey. An oil company could mount a Blackbox on an offshore oil rig to run on-site operations as well as seismic monitoring. A humanitarian organization could set up emergency data centers to coordinate relief efforts in a disaster zone. The Pentagon could deploy mobile data centers to support combat operations.

Of course, the real-world viability of these installations is only beginning to be tested. Zoning and building codes could make siting tricky in some places. And few parking lots or rooftops come ready-equipped with an industrial 600-amp power conduit, an ultrahigh-bandwidth network connection, a hefty 60-gallon-per-minute water pipe, and a large chiller to cool the water. Security fences, cameras or guards would almost certainly be desired.

MOBILE DATA CENTERS could be set up quickly at disaster zones, humanitarian aid venues or battlefields.

Nevertheless, early industry reaction has been favorable. *InfoWorld* magazine listed Project Blackbox as one of "12 crackpot tech ideas that just might work." David Patterson, a noted computer scientist at the University of California, Berkeley, who sits on Sun's technical advisory board, adds that Project Blackbox would allow companies "to put data centers closer to inexpensive or environmentally friendly sources of electricity, like a hydroelectric dam or a wind turbine." And the spread of Blackboxes, he notes, "could significantly reduce the cost of utility computing—this notion that, in the future, an iPhone or whatever will be the only thing we carry with us, and most of what we do will be an online service."

An Extended Conversation

Project Blackbox was inspired by a casual discussion two years ago between Papadopoulos and computer inventor Danny Hillis—although in truth, Hillis notes, that chat was only the latest round of a conversation that had gone on for more than a decade. The notion, he says, dates back to when he was chief scientist at Thinking Machines, Inc., a supercomputer maker in Cam-

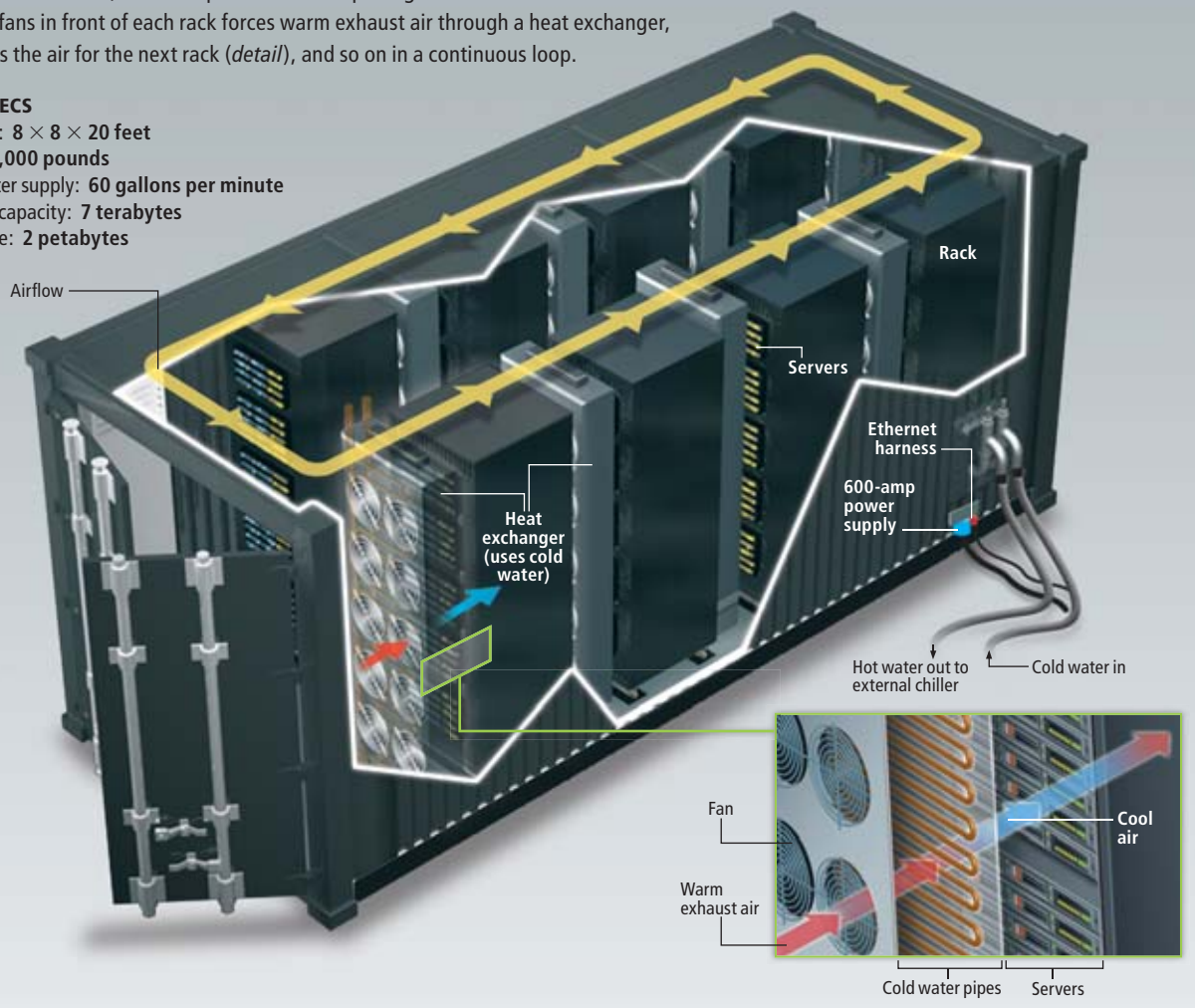
SUN MICROSYSTEMS

[HOW IT WORKS]

KEEPING COMPUTERS COOL

Inside Project Blackbox, racks of up to 38 servers apiece generate tremendous heat. A panel of fans in front of each rack forces warm exhaust air through a heat exchanger, which cools the air for the next rack (*detail*), and so on in a continuous loop.

DESIGN SPECS
Dimensions: **8 × 8 × 20 feet**
Weight: **20,000 pounds**
Cooling water supply: **60 gallons per minute**
Computing capacity: **7 terabytes**
Data storage: **2 petabytes**



5W INFOGRAPHICS/CARLOS GAMEZ/SAMUEL VELASCO (*illustration*); BEN ZWEIG (*Waldrop*)

[THE AUTHOR]

M. Mitchell Waldrop is a freelance writer in Washington, D.C., a former senior writer at *Science* magazine and author of several books, including *The Dream Machine* (Viking, 2001) about the history of computing.

bridge, Mass., and Papadopoulos was an engineer he had just hired from the Massachusetts Institute of Technology.

"A bunch of us there liked to fantasize about what the world would be like when computers were really small and cheap," Hillis says. "We loved the idea that you'd have a very simple machine on your desk and a lot of the work would be done back at some really big buildings full of computers."

Thinking Machines closed shop in 1994, but the conversation continued. A decade later Papadopoulos, who had gone to Sun when that firm bought Thinking Machines's technology, dropped by to visit Hillis at his new consulting company, Applied Minds, in Glendale, Calif. As the two men were puzzling over how to make the smallest and most energy-efficient computers possible, Hillis turned the question inside out: What was the *biggest* computer that could be built?

In practice, Papadopoulos reasoned, the biggest computer would be defined by the largest box that could be shipped around. As both men recall, that notion quickly put them onto the idea of building a system inside a shipping container. The container would *be* the computer.

This idea was not original. Brewster Kahle, another Thinking Machines alumnus, was already trying to supply developing nations with computer systems built into shipping containers. And the U.S. military had experimented with transportable data centers in trucks for field operations. But those designs had been for ad hoc, one-of-a-kind products. No one had done the serious engineering required to design a mobile data center as a mass-producible commodity.

Heat Dump

Intrigued, Papadopoulos asked Hillis and his colleagues at Applied Minds to design and build a prototype for Sun. The challenge was trickier than it might seem. Hillis could not just throw a bunch of servers into a container willy-nilly; they would fry themselves. A standard rack of modern servers consumes about 25 kilowatts of power, almost all of which ends up as heat. Conventional data centers are therefore built with plenty of space between the racks to allow for air cooling—a primary reason why data centers tend to consume so much floor space. Inside a sealed container, however, the heat would have no place to go. "That was the number-one technical challenge by far," Papadopoulos says.

After much trial and error, they found an elegantly simple solution. A standard shipping container is eight feet wide, eight feet high and 20 feet long. Up to 38 servers are stacked like pizza boxes on a frame that looks like a deep, stand-alone bookcase with no back panel. Four of these "bookcases" are spaced out along one wall [*see box on opposite page*]. A tall, water-cooled heat exchanger is sandwiched between each pair of cases. Another set of four cases and coolers stands along the opposite wall.

In this configuration, hot air from the first case of servers is vented out its back side right into the adjacent heat exchanger. The exchanger draws out the heat and sends cool air into the front of the next case. Heat exits the back of that case into the next heat exchanger, and so on, in a loop that travels down along one side of the container and back around the other side. Indeed, once the door is closed the air circulates in a continuous cycle.

The catch, of course, is that the heat exchangers must exhaust hot water outside the container to the environment or send the warmed water through an external chiller to cool and recirculate it. Either way, because the heat exchangers must absorb large amounts of heat quickly, water must flow through them at 60 gallons a minute, requiring a substantial supply pipe.

Another practical matter is bandwidth. If 10,000 company employees or Internet users are tapping into a Blackbox's terabytes of memory, its owner will have to run more than a little phone line to it. Sun recommends a dedicated fiber-optic cable. That arrangement is not too taxing for an on-site parking garage, but a downtown company that places boxes in a suburban warehouse or next to a low-cost, rural power plant will have to lease such lines from a regional telecommunications firm. Of course, an owner would have to program the system as well, but most companies choose to do this work so they can customize a data center to their needs.

Hillis's group had its prototype working well enough by spring 2006 that Sun decided to develop the system for market. Papadopoulos tapped yet another Thinking Machines alumnus to lead the development team: David Douglas, Sun's vice president of advanced technology.

"In the prototype, they got everything about 80 percent right," Douglas says. "But now my job was to figure out how we were really going to manufacture these things. How do you take empty shipping containers and stamp out data centers in high volume? How do you drive the cost down and get the reliability up?"

Engineering a Real Product

The result was an endless amount of fine-tuning, he says. Figuring out how to run the plumbing for the cooling system. Installing sensors for standing water so that a leak could quickly be detected. Providing escape routes for those times when people had to be inside a container. Finding a way to run the data cables that interconnected the servers so that someone could still pull out a unit for repair. Putting shock absorbers under each rack of computers so that they could survive the rough landings they would inevitably encounter during transport.

Finally, in October 2006, Sun unveiled the product. (The bright white container was hastily painted black for the occasion.) Papadopoulos says potential customers were intrigued—though not exactly for the reasons he initially expected.

"We were originally excited about making these systems really energy-efficient and inexpensive to operate," he says. "But the 'early adopters' we talk to are much more taken with the notion that Project Blackbox is prefab and fast. People are saying, 'I need this in 30, 60, 90 days. And I need it to *work*.'"

Sun will not discuss how many of these early adopters have actually placed orders. "Suffice it to say we have a very robust pipeline of interest," Papadopoulos notes. "These are guys who are close to meltdown," meaning they cannot add faster computers to their current systems because they have no way to exhaust the increased heat. "We expected skepticism, and we got it," he adds. "This is a radical concept in the data-center world. What we didn't expect, however, was to give a presentation and have people come up afterward saying, 'I need 10 of these tomorrow.'" ■

THE OPTE PROJECT

CLOUD COMPUTING—where people use online programs instead of their own software—could blossom if the capacity of the Internet (*modeled above by the Opte Project*) were to rapidly grow. Mobile data centers could bolster that growth.

MORE TO EXPLORE

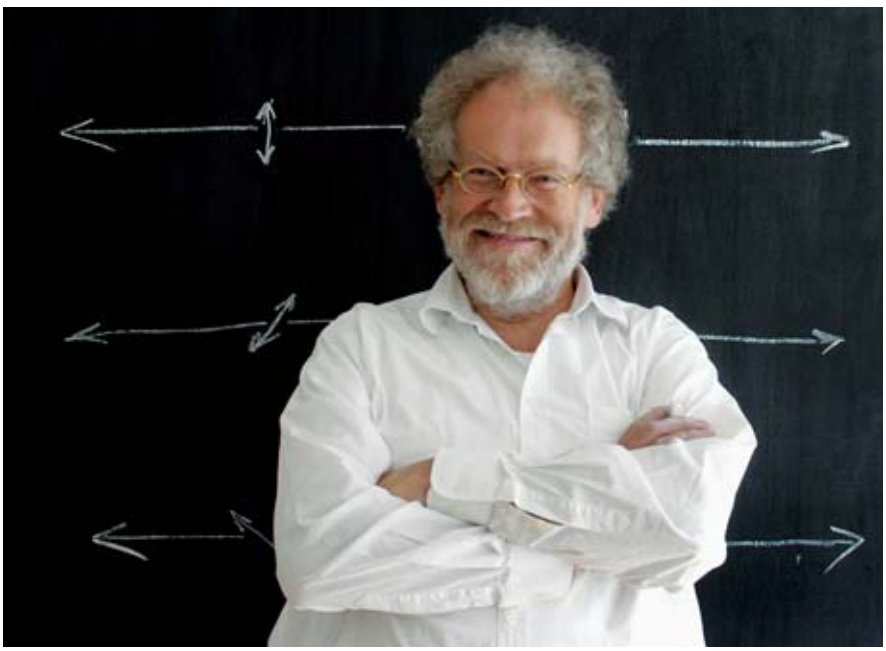
The Box: How the Shipping Container Made the World Smaller and the World Economy Bigger. Mark Levinson. Princeton University Press, 2006.

What Is Web 2.0: Design Patterns and Business Models for the Next Generation of Software. Tim O'Reilly. September 30, 2005. Available at www.oreillynet.com/pub/a/oreilly/tim/news/2005/09/30/what-is-web-20.html

Sun Microsystems's official Project Blackbox Web page: www.sun.com/emrkt/blackbox/

The *Gedanken* Experimenter

In putting teleportation, entanglement and other quantum oddities to the test, physicist Anton Zeilinger hopes to find out just how unreal quantum reality can get BY JR MINKEL



Physicist Anton Zeilinger may not understand quantum mechanics, but he has not let that stand in his path. Besides paving the way for ultrapowerful computers and unbreakable codes that run on quantum effects, the 62-year-old Austrian has a gift for pushing the limits of quantum strangeness in striking ways. Recently he observed the delicate quantum link of entanglement in light flickered between two of the Canary Islands, 144 kilometers apart. He dreams of bouncing entangled light off of satellites in orbit.

Though better known to the world at large for such headline-grabbing experiments, Zeilinger, who is based at the University of Vienna, has gone to comparable lengths to test the underlying assumptions of quantum mechanics itself. His results have left little hiding space from the conclusion that quantum reality is utterly, inescapably odd—so much so that 40 years after first encountering it as a student, Zeilinger still gropes for what makes it tick. "I made what I think was the right conclusion right away," he says, "that nobody really understands it."

For almost 17 years Zeilinger's work has centered on tricks of entangled light. Two particles are called entangled if they share the same fuzzy quantum state, meaning neither of them begins with definite properties such as location or polarization (which can be thought of as a particle's spatial orientation). Measure the polarization of one photon, and it randomly adopts a certain value, say, horizontal or vertical. Oddly, the polarization of the other photon will always match that of its partner. Zeilinger, whose group invented a common tool for entangling polarization, likes to illustrate the idea by imagining a pair of dice that always land on matching numbers.

Equally mysterious, the act of measuring one photon's polarization immediately forces the second photon to adopt a complementary value. This change happens instantaneously, even if the photons are across the galaxy. The light-speed limit obeyed by the rest of the world can take a leap, for all that quantum physics cares.

Scientists have come to view entanglement as a tool for manipulating information. A web of entangled photons might enable investigators to run powerful quantum algorithms capable of breaking today's most secure coded messages or simulating molecules for drug and materials design. For six years Zeilinger pushed the record for most number of photons entangled—three, then four (bumped to five in 2004, then six, by a former researcher in his group). In 1997 Zeilinger first demonstrated quantum teleportation: he entangled a photon with a member of a second entangled pair, causing the first photon to imprint its quantum state onto the other member. Teleportation could keep signals fresh in quantum computers [see "Quantum Teleportation," by Anton Zeilinger; Scientific American, April 2000].

A few years later his group was one of three to encode secret messages in strings of entangled photons, which eavesdrop-

JACQUELINE GODANY

ANTON ZEILINGER

QUANTUM QUESTIONER: Tests the foundations of quantum physics and the reach of quirky phenomena such as entanglement.

THE NUMBER 42: Like the answer to everything in *The Hitchhiker's Guide to the Galaxy,* quantum mechanics needs a framework to make it intelligible. Information may be the solution.

pers could not intercept without garbling the message. He is not always the first to achieve such a feat, but "he has a very good eye for an elegant experiment and one that will convey the thing that he's trying to convey," says quantum optics researcher Paul G. Kwiat of the University of Illinois, a former member of Zeilinger's lab who is now a collaborator.

"The only reason I do physics is because I like fundamental questions," Zeilinger says between bites of bagel with cream cheese and honey. He had come to Denver for a physics meeting, where he would tell assembled colleagues of his work beaming entangled photons between La Palma and Tenerife in the Canary Islands—extending the range of secret entangled messages by 10-fold.

Broad-faced and smiling, with oval glasses scrunched between his beard and a puff of frizzy gray hair, he looks a little wolflike—ready to catch quantum prey. "All I do is for the fun," he says.

Part of his fun is confirming the strangeness of quantum mechanics. Quantum indeterminacy notoriously bothered Albert Einstein, who called the theory incomplete. A particle should know where and what it is, he believed, even if we do not, and it should certainly not receive signals more quickly than at light speed.

Einstein's view remained a matter of interpretation and in the realm of *gedanken,* or thought, experiments until 1964, when Irish physicist John Bell proved that measurements of entangled particles could distinguish quantum mechanics from Einstein's position, a mix of locality (signals flow at light speed) and realism (particles possess definite, albeit hidden, properties).

Light-based tests of Bell's theorem require two detectors to rapidly switch the directions along which they measure the polarizations of entangled pairs. Statistically, local realism dictates that the polarizations can be linked, or correlated, only for a certain percentage of measurements. In a classic 1982 Bell test that set the standard for future attempts, French physicists upheld quantum mechanics—and upended local realism—by observing a greater percentage.

Zeilinger's first foray into entanglement was as a theorist, when, in 1989, he co-invented a nonstatistical version of Bell's theorem for three entangled particles—called GHZ states, after the last names of the discoverers (Daniel M. Greenberger of the City College of New York, Michael A. Horne of Stonehill College in Easton, Mass., and Zeilinger). The trio imagined three entangled photons each striking a detector set to measure polarization in one of two directions, either horizontal-vertical or twisted left or right. In principle, four combinations of detector settings would set up a single measurement capable of distinguishing quantum mechanics from local realism.

"It was the biggest advance in the whole business of the comparison of quantum mechanics to local realistic theories since Bell's original work," says physicist Anthony J. Leggett of the University of Illinois. Realizing the GHZ experiment took Zeilinger until 2000.

The year before, he also closed a loophole in the 1982 French experiment (other loopholes remain) by using two briskly ticking atomic clocks to preclude any chance that the detectors were somehow comparing notes sent at light speed.

A few months ago Zeilinger reported implementing a new kind of statistical Bell test, devised by Leggett, that pits quantum mechanics against a category of theories in which entangled photons have real polarizations but exchange hidden particles that travel faster than light. In principle, such faster-than-light theories might have perfectly mimicked quantum strangeness and let realism go unmolested. Not so, according to the experiment: the results could be explained only by quantum unreality.

So what idea replaces realism? The situation calls to mind one of Zeilinger's favorite books, the humorous novel *The Hitchhiker's Guide to the Galaxy,* by Douglas Adams, in which a mighty computer crunches the meaning of life, the universe and everything and spits out the number 42. So its creators build a bigger computer to discover the question. (An avid sailor, Zeilinger named his boat *42*.)

If quantum indeterminacy is like the number 42, then what idea makes it intelligible? Zeilinger's guess is information. Just like a bit can be 0 or 1, a measured particle ends up either here or there. But if a particle carries only that one bit of information, it will have none left over to specify its location before the measurement.

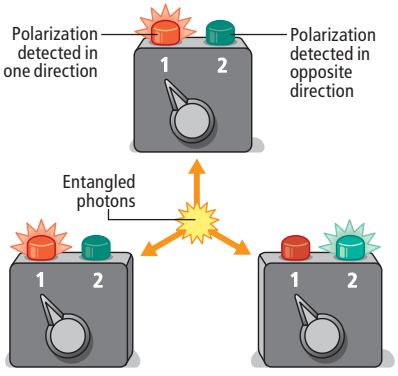
Unlike Einstein, Zeilinger accepts that randomness is reality's bedrock. Still, "I can't believe that quantum mechanics is the final word," he says. "I have a feeling that if we get really deep insight into why the world has quantum mechanics"—where the 42 comes from—"we might go beyond. That's what I hope." Then, finally, would come understanding. ■

JEN CHRISTIANSEN

[QUANTUM THREE-STEP]

Zeilinger's Reality Check

Quantum test sends three entangled photons to detectors set to measure either their horizontal or vertical polarization (*setting 1*) or their left- or right-twisted polarization (*2*). With all detectors set to 1, local realism (in which particles have "real" but hidden properties) states that one or three detectors will flash red, whereas quantum weirdness predicts two or none will. Experiments upheld the quantum view.



Other Sample Outcome Predictions

Switch setting	Quantum mechanics	Local realism
1 2 2	● ● ●	● ● ●
2 1 2	● ● ●	● ● ●
2 2 1	● ● ●	● ● ●

Blu-ray vs. HD DVD

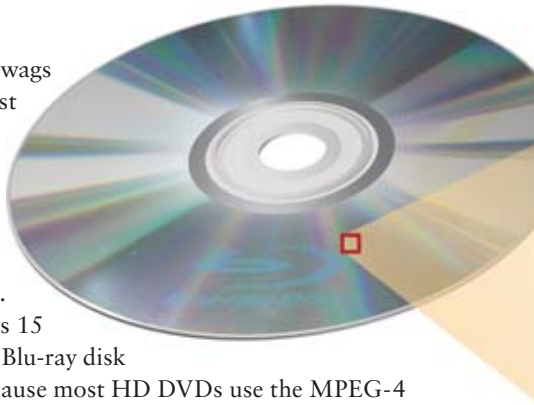
By Mark Fischetti

DVDs create sharper images than videotapes and have steadily displaced the older medium. Yet movie studios are trying to spawn a newer market by producing even higher definition video.

Disk makers have released two competing high-definition formats: Blu-ray and HD DVD. The technical press is comparing the battle with the late-1970s match between VHS and Betamax videotape standards. But the current contest may play out differently: some manufacturers are making machines that can play both formats, and Warner Brothers has announced that it will soon release movies recorded in both schemes on a two-sided disk.

"Consumers have been hesitant to jump into the high-definition market, waiting to see which format wins," says Aaron Dew, product development manager at LG Electronics USA in Englewood Cliffs, N.J. "Frankly, the competition has held the market back." In February, LG began shipping a player that can read both formats. Critics say the hybrid machines may not be optimized for either Blu-ray or HD DVD—or will cost more if they are—and that two-sided disks will be more expensive because a studio must record each disk twice.

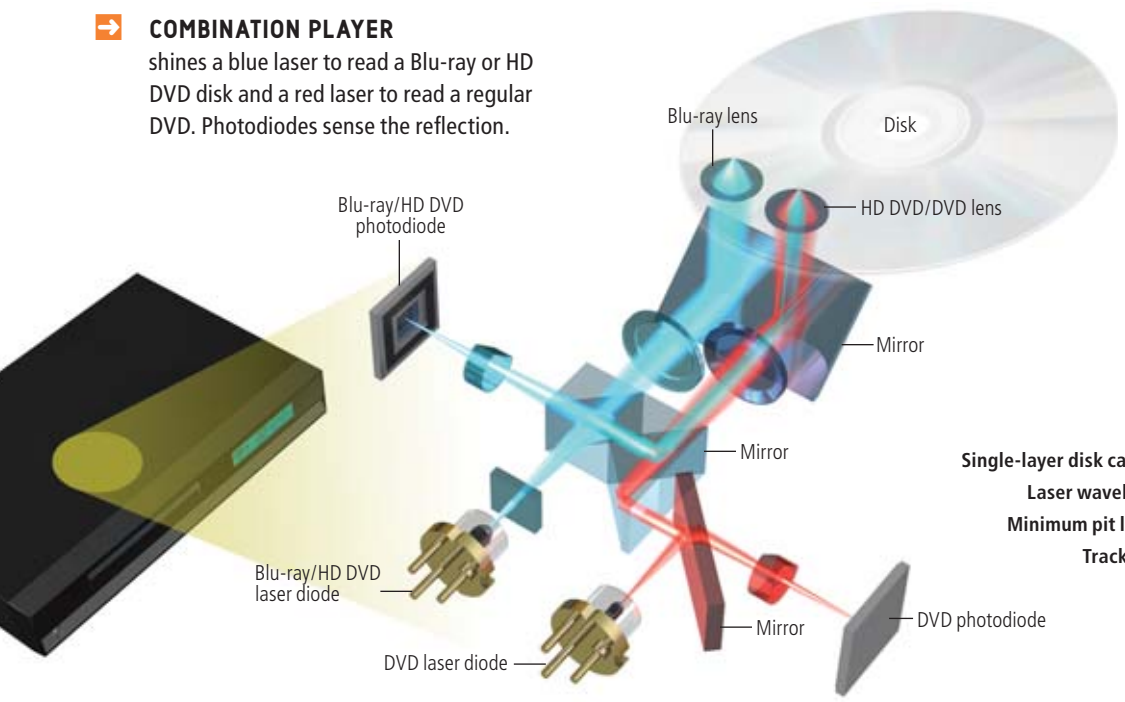
Blu-ray and HD DVD produce equally sharp images. The quality of imagery as compared with that produced by standard DVD is not as dramatic as the improvement DVD provides over videotape, however, and some wags wonder if such a modest gain is worth the cost of players and disks.

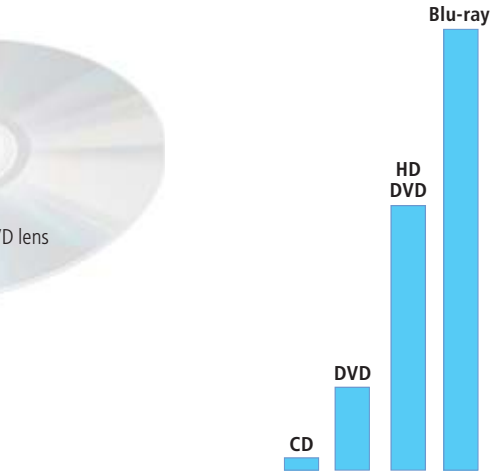


Undaunted, the two camps are now trying to distinguish themselves in a capacity race. An HD DVD disk holds 15 gigabytes of data, and a Blu-ray disk holds 25 gigabytes. Because most HD DVDs use the MPEG-4 data-compression scheme rather than the MPEG-2 scheme still used by most Blu-ray disks, however, both are sufficient to store full-length movies plus some extra features. Makers have also begun offering so-called dual-layer disks that double those capacities on a single side. Although the hike allows even more extras and advanced audio to be added, "there is a little bit of 'mine is bigger than yours,'" notes Steve Wyatt, global marketing director for media at GE Plastics in the Netherlands. Some makers have even prototyped triple-layer disks.

Combination players and two-sided disks suggest both formats could coexist. "But if manufacturers want to keep it simple for the consumer and for retailers," Wyatt proposes, "one format is better than two."

COMBINATION PLAYER shines a blue laser to read a Blu-ray or HD DVD disk and a red laser to read a regular DVD. Photodiodes sense the reflection.

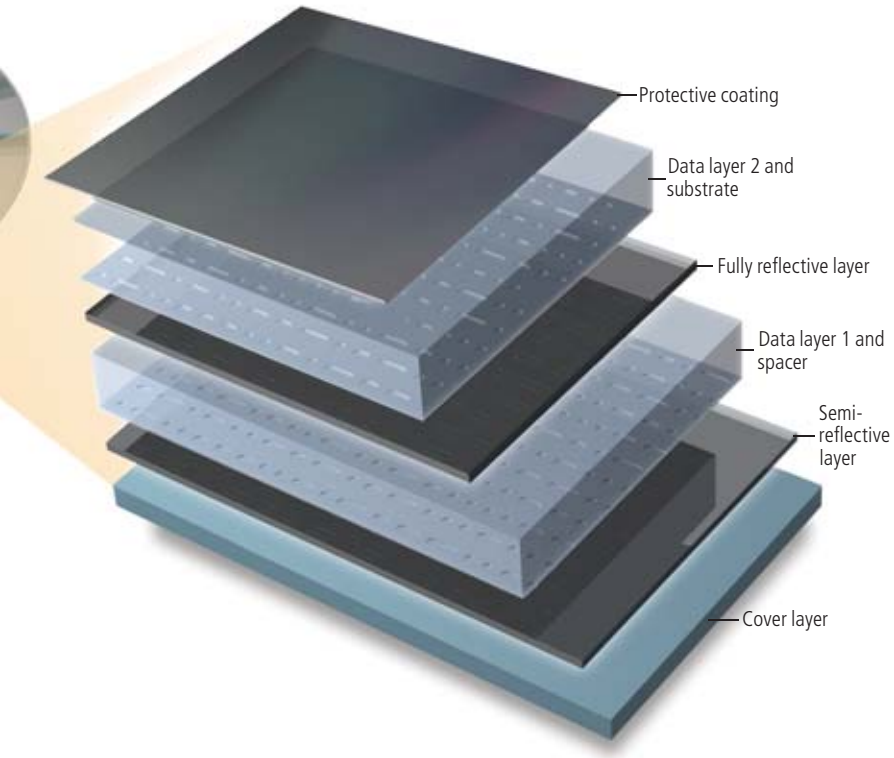


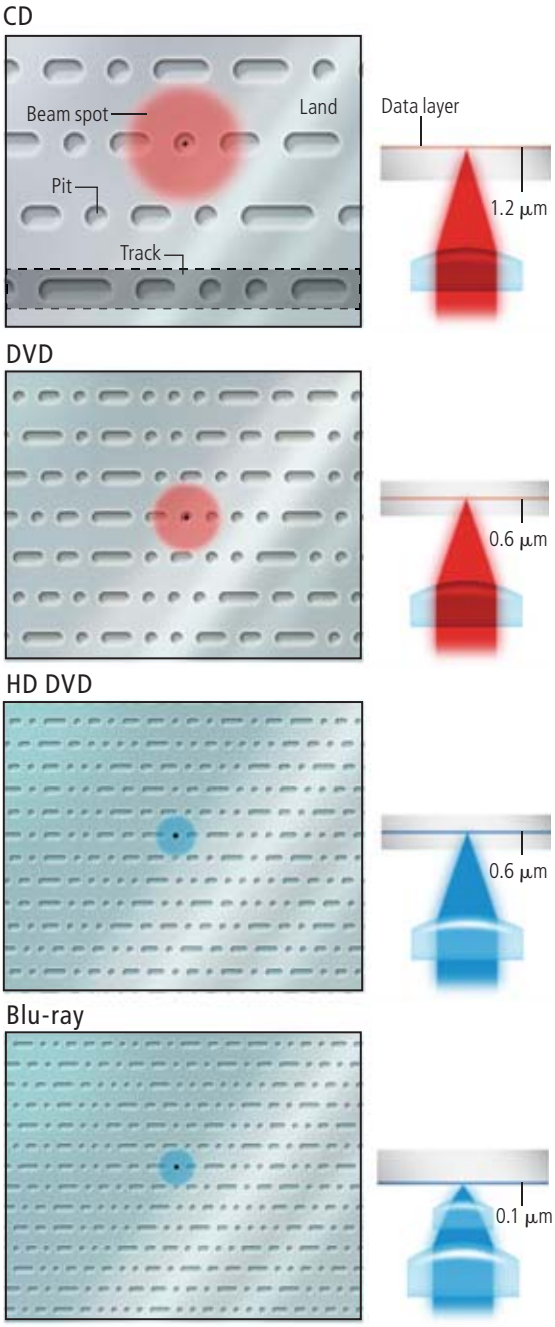


	CD	DVD	HD DVD	Blu-ray
Single-layer disk capacity (GB)	0.7	4.7	15	25
Laser wavelength (nm)	780	650	405	405
Minimum pit length (μm)	0.8	0.4	0.2	0.15
Track pitch (μm)	1.6	0.74	0.4	0.32

SW INFOGRAPHICS/PEDRO VELASCO/SAMUEL VELASCO; SOURCE: LG ELECTRONICS (*player*)

DUAL-LAYER BLU-RAY DISK
stores data at two levels, which are read by a laser that reflects off both.





BLU-RAY AND HD DVD DISKS
pack more data than CDs or DVDs. The data pits, which constitute the digital 1s and 0s, can be smaller because they are read by a blue-violet laser, which has a shorter wavelength than a red laser. Positioning the data layer closer to the laser (*as shown at right*) also enables a tighter focus and less distortion and thus smaller pits and tracks.

DID YOU KNOW...

PROGRESSIVE PRICE: Blu-ray and HD DVD can be shown only at full resolution on high-definition digital displays. The best displays have a maximum resolution of 1,080p, in which there are 1,080 rows of pixels and each row is energized progressively (thus the "p"). Slightly less sharp is a resolution of 1,080i, in which alternating rows are energized, or interlaced (thus the "i"). Blu-ray players typically output a 1,080p signal, whereas some HD DVD players deliver 1,080i. High-definition television (HDTV) signals are broadcast at 1,080i or 720p. Thus, paying extra for a 1,080p TV offers no advantage for current HDTV or certain high-definition players.

R U CLEAR? The shorthand for CD and DVD varieties can be confusing, and the puzzle continues for high-definition formats. A Blu-ray disk is designated BD. One that is BD-ROM only plays the material prerecorded on it. A BD-R disk can be recorded on only once. A BD-RE can be rerecorded multiple times. Similar flavors for Blu-ray's competitor are HD DVD-ROM (prerecorded), HD DVD-R (recordable once) and HD DVD-RAM (rerecordable).

DVDs SPARED: So that consumers will not have to stack two machines, or discard their old DVDs, the industry has prototyped backward-compatible high-definition disks and players. The disks contain an added layer that holds traditional DVD data, and the players can read both formats.

SEND TOPIC IDEAS TO
workingknowledge@SciAm.com

Cosmic Questions ▪ Baboon Melodrama ▪ Cold Coors

BY MICHELLE PRESS

COSMIC JACKPOT: WHY OUR UNIVERSE IS JUST RIGHT FOR LIFE

by Paul Davies. Houghton Mifflin, 2007 ($26)

The head of a new cosmology think tank—provocatively named Beyond—at Arizona State University, physicist Paul Davies says he wants to look into "the origin of the universe, life, consciousness and the emergence of humanity." In this, his 27th book, Davies examines the perplexing fact that many basic features of the physical universe seem tailor-made to produce life. He embraces the so-called anthropic principle: the idea that the universe's suitability for intelligent life is not an accident but a logical development. In accessible, relatively jargon-free language, he summarizes the current state of knowledge in cosmology and provides an introduction to particle physics. He then asks the question: Does the design of the universe imply the existence of an intelligent designer? Davies comes down on the side of some sort of undefined "life principle" in the cosmos, but he says that this "is something I feel more in my heart than in my head."

BABOON METAPHYSICS: THE EVOLUTION OF A SOCIAL MIND

by Dorothy L. Cheney and Robert M. Seyfarth. University of Chicago Press, 2007 ($27.50)

In one of his notebooks, Charles Darwin wrote: "Origin of man proved.—Metaphysic must flourish.—He who understands baboon would do more towards metaphysics than Locke." Robert M. Seyfarth and Dorothy L. Cheney—pioneers in the study of primate psychology—take up the challenge. Baboons live in groups of up to 100, which include a few males and eight or nine matrilineal families of females. Daily life encompasses intrigues that range from alliances of three individuals up to battles that involve three or four extended families. Paste on top of this a complicated mix of personal relationships—from short-term bonds for mating to long-term friendships that lead to cooperative child rearing—and the result "is a kind of Jane Austen melodrama," in which each individual must predict the behavior of others and take care to form the most advantageous relationships. Any way you look at it, the authors say, most of the problems facing baboons can be expressed in two words: other baboons. The authors aim to understand the intelligence that underlies this social organization: How do baboons conceive of the world and their place in it? Do they understand kinship relations? How do they infer the motives of others?

EXCERPT

THE SNORING BIRD: MY FAMILY'S JOURNEY THROUGH A CENTURY OF BIOLOGY

by Bernd Heinrich. Ecco, 2007 ($29.95)

"Mamusha is just settling down on her bed to watch the evening news when I arrive. Two cans of Coors, which she has opened with the point of a pair of scissors, are on the table next to her, along with a box of German chocolates. She used to make her own beer, but now, in her mid-eighties, she likes Coors from a can; and because her gnarled hands are too weak, she cannot pull off the tabs. Duke, the huge shepherd-hound that she rescued from the pound, is at her feet, and a one-legged chicken lies cradled in her lap. She is mildly irritated at me for arriving unannounced … but soon I have placated her and she offers me a beer."

How can you resist an opening paragraph like this? Bernd Heinrich (a professor of biology at the University of Vermont and author of several best-selling books) relays the adventures of his father, Gerd, a naturalist who, among other things, captured a rare rail called the snoring bird in the jungles of Sulawesi, flew a Junkers for the Luftwaffe in World War I, and at the end of World War II rescued his family from the invading Red Army and lived in the woods of northern Germany for five years until they could emigrate to the U.S.

SNORING BIRD

NEW AND NOTABLE BOOKS FOR SUMMER READING

1 **Where's My Jetpack? A Guide to the Amazing Science Fiction Future That Never Arrived**
by Daniel H. Wilson, illustrated by Richard Horne. Bloomsbury, 2007 ($14.95)

2 **Brave New Words: The Oxford Dictionary of Science Fiction**
by Jeff Prucher. Oxford University Press, 2007 ($29.95)

3 **Fly Me to the Moon: An Insider's Guide to the New Science of Space Travel**
by Edward Belbruno. Princeton University Press, 2007 ($19.95)

4 **The Hazards of Space Travel: A Tourist's Guide**
by Neil F. Comins. Villard, 2007 ($19.95)

5 **The New Time Travelers: A Journey to the Frontiers of Physics**
by David Toomey. W. W. Norton, 2007 ($25.95)

6 **The Darwin Awards 4: Intelligent Design**
by Wendy Northcutt, with Christopher M. Kelly. Dutton, 2006 ($19.95)

7 **The Songs of Insects**
by Lang Elliott and Wil Hershberger. With photographs and sound recordings. Houghton Mifflin, 2007 ($19.95)

8 **Sixty Days and Counting**
by Kim Stanley Robinson. Bantam, 2007 ($25) (Science fiction, and Robinson knows the science behind the fiction.)

9 **Death by Black Hole: And Other Cosmic Quandaries**
by Neil deGrasse Tyson. W. W. Norton, 2007 ($24.95)

Why is there an ozone hole in the atmosphere when there is too much ozone at ground level?

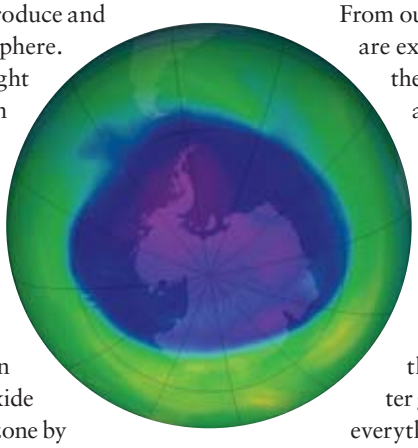
—H. Cox, San Antonio, Tex.

Ross J. Salawitch, a senior research scientist at NASA's Jet Propulsion Laboratory in Pasadena, Calif., explains:

The abundance of atmospheric ozone (O_3) is relative—levels that are dangerously high in the atmosphere's lowest layer, the troposphere, would be dangerously low in the stratosphere, one layer above. As such, ground-level ozone is not plentiful enough to fill the so-called ozone hole. In addition, ozone is regulated primarily by local chemical processes, and a temperature barrier at the troposphere-stratosphere border prevents a large-scale mixing of ozone across atmospheric levels.

Stratospheric ozone provides a shield from harmful ultraviolet solar radiation. Conversely, elevated levels of tropospheric ozone can lead to human health problems and damage to crops and forests.

Natural processes continuously produce and remove ozone throughout the atmosphere. In the stratosphere, ultraviolet sunlight breaks down some molecular oxygen (O_2); the separate oxygen atoms then recombine with another oxygen molecule to form ozone.



Some industrial pollutants, such as chlorofluorocarbons (CFCs), are able to reach the stratosphere because they are nonreactive in the troposphere. Eventually they break down into molecules such as chlorine monoxide (ClO), which depletes stratospheric ozone by transforming it back into molecular oxygen.

Stratospheric ozone levels are typically about 400 Dobson units (DU), the standard unit of ozone concentration. Every spring over Antarctica, extremely cold conditions enable chemical reactions that produce very high levels of ozone-destroying ClO. Within the Antarctic ozone hole, levels can drop to 85 DU.

Typical tropospheric ozone levels are only about 25 DU but depend greatly on local conditions. Natural ozone production in the troposphere is inefficient because the intensity of ultraviolet sunlight is very low. Human activities such as fossil-fuel combustion and biomass burning lead to elevated levels of carbon monoxide, hydrocarbons and nitrogen oxides—gases that participate in a series of chemical reactions that produce tropospheric ozone.

The Montreal Protocol has banned production of CFCs throughout the world, and the stratospheric ozone layer is expected to recover over the next 50 to 100 years. Efforts are being undertaken to implement emission-control strategies that will limit tropospheric ozone to less than prescribed levels. These initiatives are challenged by global industrialization and the fact that tropospheric ozone is affected by pollutants emitted both locally and from distant upwind sources, even other countries or continents.

How does catnip work its magic on cats?

Ramona Turner, a longtime veterinarian who owns two Fresno, Calif.–based animal hospitals, replies:

From our small domestic companions to the largest lions, cats are exquisitely susceptible to nepetalactone, a compound in the stems and leaves of the catnip plant that essentially acts as an artificial feline pheromone.

Nepetalactone in the catnip enters the animal's nasal tissue, where it is believed to bind to protein receptors that stimulate sensory neurons. These cells trigger a cascade of responses that eventually reach the amygdala (two neuronal clusters in the midbrain that mediate emotional responses to stimuli) and the hypothalamus (the brain's "master gland" that plays a role in regulating everything from hunger to emotions). The amygdala integrates the information flow, and its neurons project to areas governing behavioral responses. The hypothalamus regulates neuroendocrine responses through the pituitary gland, creating a sexual response to the artificial pheromone.

When cats smell catnip, they exhibit several telltale behaviors: they may rub their heads and body on the herb or jump, roll around, vocalize and salivate. This response lasts for about 10 minutes. About 70 to 80 percent of cats demonstrate this hereditary reaction to the plant's presence but not before they are a few months old. ■

NASA (ozone hole); CLAY PERRY Corbis (catnip)

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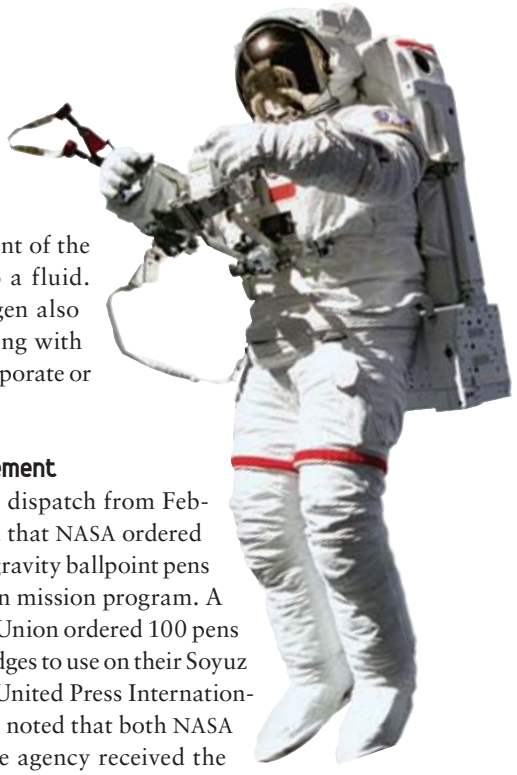
Q *NASA* ***Spent Millions*** *on a Pen Able to* ***Write in Space***

BY CIARA CURTIN



During the height of the space race in the 1960s, legend has it, NASA scientists realized that pens could not function in zero gravity. They therefore spent years and millions of taxpayer dollars developing a ballpoint pen that could put ink to paper without needing gravitational force to pull on the fluid. But their crafty Soviet counterparts, so the story goes, simply handed cosmonauts grease pencils. Did NASA really waste that much money?

The Space Pencil

Originally American astronauts, like the Soviets, wrote with pencils, according to NASA historians. Indeed, in 1965 NASA ordered 34 mechanical pencils from Tycam Engineering Manufacturing in Houston at $128.89 apiece: $4,382.50 in total. When these sums became public and caused an outcry, NASA scrambled to find a cheaper alternative.

Pencils may not have been the best choice anyway. The tips could flake or break off, drifting in microgravity where they might harm an astronaut or equipment. And pencils are flammable—a characteristic NASA wanted to avoid in onboard objects after the *Apollo 1* fire.

The Space-Age Ballpoint

Meanwhile Paul C. Fisher and his business, Fisher Pen Company, had invested a reported $1 million (none of it from NASA) to create what is now commonly known as the space pen. The device, patented in 1965, could write upside down, in frigid or roasting conditions (down to –50 degrees Fahrenheit or up to 400 degrees F), and even underwater or submersed in other liquids. If too hot, though, the ink turned green instead of its normal blue.

Fisher offered the implement to NASA. Because of the earlier mechanical pencil fiasco, the agency hesitated. But after testing the tool—named the AG-7 "Anti-Gravity" Space Pen—the U.S. decided in 1967 to use it on future spaceflights. Fisher's pen makes up for a lack of gravity by storing ink in a cartridge pressurized with nitrogen at 35 pounds per square inch—more than twice as much force as sea-level atmospheric pressure on Earth. This pressure pushes the ink toward the tungsten carbide ball at the pen's tip.

The ink, too, differs from that of other pens. It stays a gel-like solid until the movement of the ballpoint turns it into a fluid. The pressurized nitrogen also prevents air from mixing with the ink, so it cannot evaporate or oxidize.

International Agreement

An Associated Press dispatch from February 1968 reported that NASA ordered 400 of Fisher's antigravity ballpoint pens for the Apollo moon mission program. A year later the Soviet Union ordered 100 pens and 1,000 ink cartridges to use on their Soyuz space missions, the United Press International said. The AP later noted that both NASA and the Soviet space agency received the same 40 percent discount for buying their pens in bulk. They both paid $2.39 per pen instead of $3.98—nowhere near millions.

The space pen's mark on the Apollo program was not limited to facilitating writing in microgravity. According to its maker, the *Apollo 11* astronauts, who were the first to walk on the moon, also wielded the pen to fix a broken engine-activating switch on the lunar module—a repair that enabled them to lift off from the moon for their rendezvous with the mother ship and their return to Earth.

Since the late 1960s American astronauts and Russian cosmonauts have used Fisher's pens. In fact, Fisher has created an entire line of space pens. A newer version, called the Shuttle Pen, served on NASA's space shuttles and on the Russian space station, Mir. Of course, you don't have to go into orbit to get your hands on a space pen—earthbound folks can own one for the low, low price of $50.

Ciara Curtin is a freelance science journalist based in New York City.

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NASA (*astronaut*); FISHER SPACE PEN (*pen*)