Intelligence Genes: The Elusive Biology of IQ (*page 52*)

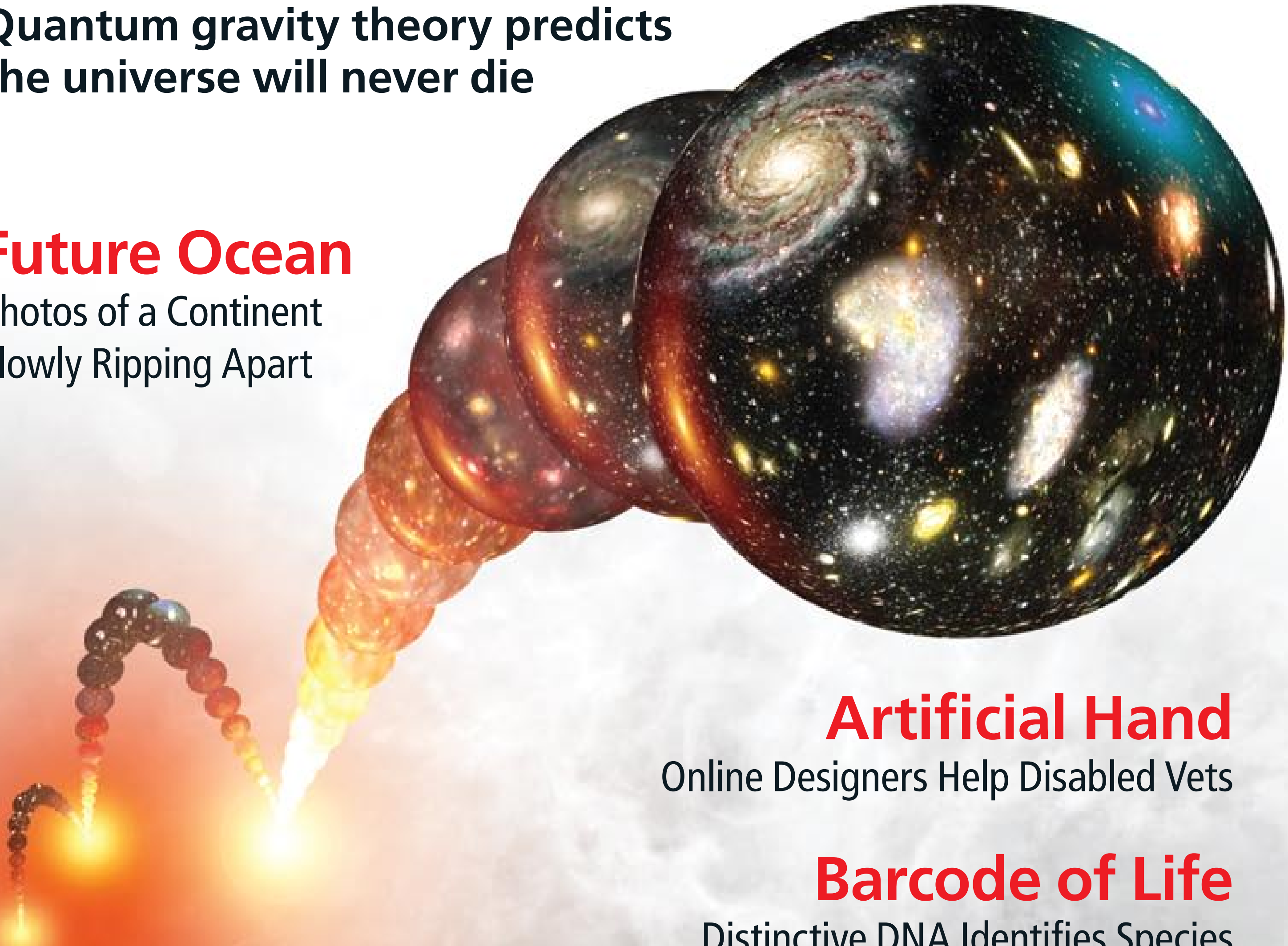
SCIENTIFIC AMERICAN

Benefits of the New WEB SCIENCE
page 60

October 2008 www.SciAm.com

Forget the Big Bang: Now It's the BIG BOUNCE

Quantum gravity theory predicts the universe will never die



Future Ocean
Photos of a Continent Slowly Ripping Apart

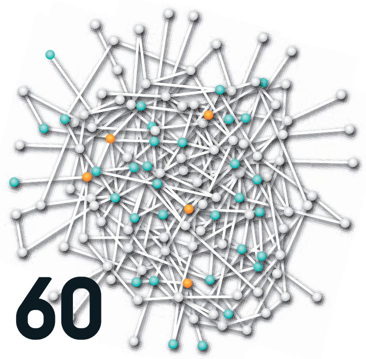
Artificial Hand
Online Designers Help Disabled Vets

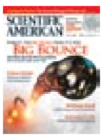
Barcode of Life
Distinctive DNA Identifies Species

FEATURES

SCIENTIFIC AMERICAN October 2008 ■ Volume 299 Number 4

Image by Kenn Brown





ON THE COVER

One theory of quantum gravity suggests that the cosmos oscillates in size without ever reaching the infinite density associated with the big bang. Image by Kenn Brown, Mondolithic Studios.

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IN-DEPTH REPORT: SCIENCE AND THE PRESIDENTIAL ELECTION ▼

Find out which congressional district races may hinge on science issues and what the candidates have to say about the environment. More at **www.SciAm.com/election2008**

DARREN HAUCK *Corbis*

News
Hydrogen Power on the Cheap—Or, at Least, Cheaper
Chemists have devised less expensive ways to tap the energy potential of this ubiquitous element.

Podcast
Outsmarting Bombers and a Warless Future?
We discuss high-tech attempts to battle improvised explosive devices (IEDs), and journalist John Horgan talks about the possibility of eliminating war.

News
How the Seeds of the First Stars Formed
Simulations reveal that the cosmic dark ages ended when protostars coalesced from primordial clouds of hydrogen gas.

Video
Instant Egghead
From dark matter to synthetic biology, SciAm editors show how to explain complicated concepts simply, using the everyday stuff on their desks.

News
Could a Pill Replace Exercise?
A drug improves physical endurance in mice, but don't throw away your treadmill quite yet.

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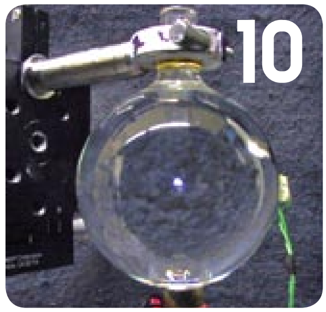
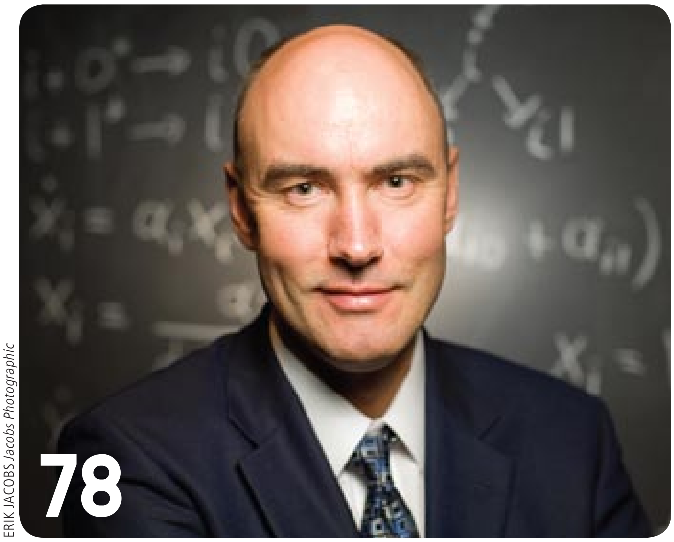
DEPARTMENTS





ERIK JACOBS *Jacobs Photographic*

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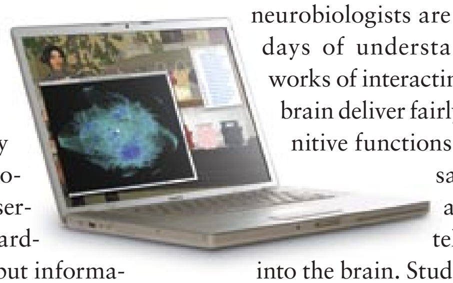
All Together Now

Understanding how novelty emerges from complex systems is a new frontier

Remember synergy? It was one of the buzziest buzzwords energizing the dot-com era of the late 1990s. The Internet was making it easier than ever to pull people and organizations into cooperative networks, and legions of start-up companies exuberantly leapt in to take advantage of the new efficiencies and marketing opportunities. Expectations were rife that the whole would exceed the sum of the parts, although proponents were sometimes vague about how (and how to build a real business proposition around it).

One decade and a boom-and-bust cycle later, the synergistic promise of the Internet is in force. Thanks to the collaborative enterprises of Web 2.0, people routinely reveal their life histories on Facebook, share photographs via Flickr, contribute to wikis, and Twitter their passing thoughts to anyone who will read them. Synergy may take a backseat to "social networking" and "user-generated content" as boardroom jargon these days, but information technology has indeed made this a golden era for collaboration.



Tim Berners-Lee, the author of the Web's technical protocols, believes that the phenomenon of the Web's growth deserves its own study, as he advocates with Nigel Shadbolt in their article, beginning on page 60. Something has made the Web fantastically successful at inspiring and empowering innovation; the trick is to find out which of its features have been most instrumental to that end so that they might be enhanced further or duplicated in other situations.

As an example of the enterprises emerging spontaneously through the Web, Shadbolt and Berners-Lee do not cite the Open Prosthetics Project, which journalist Sam Boykin writes about in "With Open-Source Arms," but they could have. As battlefield veterans and accident survivors who have lost their arms know tragically well, the available prosthetic limbs are poor substitutes. Unfortunately, because the commercial market for such prosthetics is so small, improvements have been slow to materialize. Recently, however, a community of sympathetic designers has started working on the problem, modeling their Web-based collaboration on open-source software projects. Boykin describes some of their amazing progress to date, starting on page 72.

Perhaps it is just wishful thinking, but I suspect that study of digital networks and their emergent properties may someday yield a premium of insights into how biological networks behave, too. Certainly there is no shortage of mysteries in that area that need illuminating. For instance, neurobiologists are still in the early days of understanding how networks of interacting neurons in the brain deliver fairly elementary cognitive functions. No one can yet say how a quality as abstract as intelligence is wired into the brain. Studies have nonetheless shown rather conclusively that some component of intelligence as measured by IQ tests is hereditary and so must be represented in our genes.

Yet as science writer Carl Zimmer explains in his article on "The Search for Intelligence" (*page 52*), the nature of that genetic component is hard to pin down. Researchers can point to specific bits of DNA that can each add a tiny amount to IQ but to never more than a few points. Unless those studies are missing something, the totality of those genes somehow gives intelligence a boost that exceeds the sum of their individual contributions. So whether or not it is a currently faddish buzzword, we all have synergy on the brain. ■

JOHN RENNIE
editor in chief

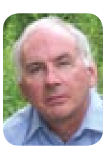
FLYNN LARSEN (*Rennie*); CARY WOLINSKY (*photoillustration*); MATTHEW HURST (*blogosphere visualization*)

Among Our Contributors

TIM BERNERS-LEE invented the World Wide Web. He also founded the international World Wide Web Consortium, which maintains consistent technical standards online.

MARTIN BOJOWALD of the Institute for Gravitation and the Cosmos at Pennsylvania State University has pioneered the application of loop quantum gravity theory to cosmology.

EITAN HADDOK is a Paris-based photographer and reporter who specializes in coverage of earth science and the environment.



PAUL D. N. HEBERT originated the concept of DNA barcoding for identifying species. He directs the Biodiversity Institute of Ontario and holds a position at the University of Guelph.

CARL ZIMMER is an award-winning science journalist and blogger. Of his seven books, the most recent is *Microcosm: E. coli and the New Science of Life.*

Climate Change Ethics ▪ Trust ▪ Baby Universes

JUNE 2008

"In light of continued global-level ecological degradation and climate change pressures, surely we must face the possibility that those who come after us will be worse off."
—*Don Clifton*
BRIGHTON, SOUTH AUSTRALIA

Discounting the Future

In "The Ethics of Climate Change," John Broome argues on moral grounds against economists who claim that the need to take immediate action against climate change is not urgent. But Broome does not adequately scrutinize the common assumption of economists that future generations will be wealthier. In light of continued global-level ecological degradation and climate change pressures, surely we must face the possibility that those who come after us will be worse off.

Another unchecked assumption is that discounting (considering future benefits to be worth less than those received today) is a valid mechanism to apply across generations. Although discounting may be appropriate when costs and benefits can be internalized to one entity, it is a different story when costs are imposed on parties who have no say in the matter.

Don Clifton
Brighton, South Australia

Broome errs in assuming the discount rate applies only to the value of *goods*. Discounting should include the value of *services*. A forest, for example, is an essential habitat and thus has a value beyond the present and future price of lumber. Shouldn't we adopt an *appreciation rate* for the earth's life-support systems?

Paul R. Epstein
Center for Health and the Global Environment
Harvard Medical School

BROOME REPLIES: *I agree with Clifton that our projections for economic growth need scrutiny in light of climate change. But that is not a job for me as a philosopher; I can only report predictions that have been derived from existing economic models. I also agree that we need to think about the value of goods for future people in a different way from how we think about the value of our own future goods. The methods of ethics equip us to do that. Economists who ignore ethical considerations might justly be accused of ignoring Clifton's criticism.*

Epstein is right to point out that talk of a single discount rate is an oversimplification. Different commodities should be discounted at different rates. Scarce resources should be discounted at lower rates than produced goods—generally at or below zero.

Trust or Generosity?

Paul J. Zak's use of the term "trust" to describe the state he investigates in "The Neurobiology of Trust" might be problematic. His studies rely heavily on an iteration of the trust game in which subject 1 decides how much of $10 to anonymously give an unknown subject 2. Subject 2 receives triple that plus $10 and decides how much to give back. What may actually be measured by this game is "generosity," which imperfectly overlaps with trust. Moreover, trust and generosity can vary with circumstance and contingency. Many subject 1s might offer $5 in Zak's game. But if the game involved $10,000, I doubt that many would offer half that sum.

Barry M. Maletzky
Oregon Health Sciences University

NEUROCHEMICAL oxytocin has been linked to an individual's propensity to trust a stranger.

ZAK REPLIES: *The beauty of using the trust game in our experiments is that it has been run many times in many variations and with relatively high stakes, including potential returns of $100 in the U.S. and an average three-month salary in eastern European countries. In each case, nearly all subject 1s chose to send money to a stranger. This transfer captures the essence of trust: it leaves one open to exploitation on the expectation of receiving a return. People seem to understand intuitively how to induce another person to reciprocate. This phenomenon is not generosity, because in the trust game a return is expected, whereas that is not the case when one is being generous. For further discussion of these distinctions, see my* PLoS One *paper on generosity, available at http://tinyurl.com/5hrlme*

Where Babies Come From

In "The Cosmic Origins of Time's Arrow," Sean M. Carroll questions why we perceive time as only moving forward and posits that our universe is part of a multiverse containing universes in which time moves either forward or backward. In this scenario, baby universes fluctuate out of a starting point of empty space.

But wouldn't quantum fields experience thermal fluctuations in nonempty space as well? Is there something special about empty space that would give rise to the baby universes?

Michael Jacob
Oakland, Calif.

CARROLL REPLIES: *The important feature of nonempty universes is that they do not stay put—according to general relativity, a universe with matter will either expand and empty out or contract and get much denser, crashing to a singularity in a finite amount of time. So the only state in which spacetime can persist for an indefinite period is a state of emptiness.*

It is very likely that the kinds of quantum fluctuations required to make a baby universe could happen in a universe with matter as well, but such fluctuations are exceedingly rare. In an empty universe you have forever to wait. Universes with matter in them do not last long enough for such fluctuations to be important.

The L Word

As a former resident of the Gillis W. Long Hansen's Disease Center in Carville, La., I take strong exception to the use of the word "leper" (which I refer to as "the L word") in "Care of Lepers," a 1908 article on the opening of the Culion Hospital in the Philippines, compiled by Daniel C. Schlenoff [50, 100 and 150 Years Ago]. Such hospitals were primarily built because of stereotypes held by the medical community and general public about Hansen's disease as a fearful condition that required the banishment of persons affected by this misunderstood illness. This stereotype continues because references stigmatize us as "lepers" rather than as individuals battling a bacterial infection.

José P. Ramirez, Jr.
Managing editor
The Star

ERRATUM "The Tunguska Mystery," by Luca Gasperini, Enrico Bonatti and Giuseppe Longo, provides incorrect coordinates for Lake Cheko in Siberia. The correct coordinates are 60°57′50.40″ N, 101°51′36.01″ E.

CLARIFICATION "First Artificial Enzyme" [Updates] reports on a man-made enzyme that removes a proton from a carbon atom. Specifically, the enzyme removes a hydrogen ion from one of the carbon atoms in a benzene ring. When chemists refer to the removal and addition of protons, they are usually describing the bonds between elements, rather than the atomic nucleus as in nuclear physics terminology.

Letters to the Editor

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Letters may be edited for length and clarity. We regret that we cannot answer each one. Join the discussion of any article at www.SciAm.com/sciammag

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MARK ANDERSEN *Getty Images (woman)*; RYAN MCVAY *Getty Images (man)*

Star Power ■ Car Thieves ■ Expensive Horse-Power

Compiled by Daniel C. Schlenoff

OCTOBER 1958

FUSION WORK—"Last month, at the second Geneva conference on atomic power, the fusion reactions were at the center of the stage. The knotty and often profound questions encountered in the research engaged a substantial portion of the formal and informal discussions. The elaborate experimental gear exhibited by the United Kingdom, the U.S. and the U.S.S.R. testified to the huge scale of the programs the major nuclear powers have been conducting, until recently in secret. Among the several approaches of the U.S. program publicly disclosed in detail for the first time at Geneva is the 'stellarator.' It is the work of Project Matterhorn at Princeton University and embodies some of the things we have learned from theoretical and experimental investigations conducted since 1951. —Lyman Spitzer, Jr."

OCTOBER 1908

HORSELESS CARRIAGE THIEVERY—"A motor-car lock which will be simple and thief-proof would be an invention which would appeal to motorists just now, and the wonder is that some such device has not already been included in the regular equipment of some make of car. It may be true that in some cities the removal of the starting crank or a spark plug is a guard against theft, but thieves are too often graduates of factories and several instances have occurred of late in which the thief has supplied the spark plug himself."

BOTANICAL READERS—"A Javanese subscriber of this journal, Mr. Bruysman of Nongho Djadjar, near Lawang, Java, sends us an interesting communication on an experimental botanical garden which he established at an altitude of 4,000 feet. The climate, he writes, is ideal. Even the wet season lasting from November to April is not too unpleasant despite the daily rains. Mr. Bruysman is growing hundreds of tropical, European, Asiatic, American, and Australian plants, his purpose being to collect medicinal, ornamental, and useful plants from all quarters of the globe. He has been assisted by many botanists, and asks that the readers of this journal help him in his work by sending seeds and specimens."

EGYPTIAN FOSSILS—"Prof. Henry F. Osborn, who directed the expedition of the American Museum of Natural History to the Fayum Desert of Egypt, is just now placing on exhibition one of the most important and significant finds there, the skull of the giant Arsinoitherium, one of the most extraordinary land mammals of ancient Africa. The dominating and all-powerful feature of the Arsinoitherium was the long pair of sharp-pointed horns protruding upward and outward for nearly two feet, an appendage both dangerous and fantastic. The spirited and realistic restoration of this giant is seen in the accompanying drawing by Mr. Charles R. Knight."

ARSINOITHERIUM, an extinct mammal of the Eocene, in a lively artistic interpretation from 1908

Images of the skull are available at www.SciAm.com/oct2008

OCTOBER 1858

ACID AIR—"Housekeepers will, without doubt, thank us for informing them that the black sulphide of silver, which forms on plated and silver wares, door plates and knobs, may at once be removed by wiping the surface with a rag wet with aqua ammonia (the ammonia should be very weak). This black film is no evidence that the silver is impure, for it forms as quickly on fine silver as on that which is alloyed with copper. After rain, much sulphide of hydrogen is disengaged from the soil of our streets."

CHEAP FUEL FARMING—"The 'iron horse' seems to be gradually claiming the attention of farmers, for the purpose of tilling the soil. The Royal Agricultural Society of England has recently awarded a prize of $2,500 to Mr. H. Fowler, for the most efficient steam plow. It has a stationary engine, using warping ropes to drag the shares through the furrows. Mr. John Joseph Mechi, the celebrated English farmer, uses one of these plows; and its cultivation of the soil is very superior—the yield of wheat having been increased eight bushels per acre by its use. The saving is about one-fourth of the cost, in comparison with horses. Where fuel is abundant and cheap, we have no doubt that in twenty years hence, steam plows will be in common use in our great Western prairies."

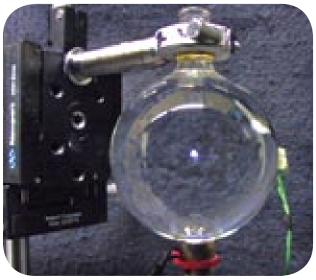
SCIENTIFIC AMERICAN, VOL. XCIX, NO. 16; OCTOBER 17, 1908

Bubble Fusion ▪ Tortoise Triumph? ▪ Virus-Infecting Viruses ▪ Cheaper LEDs

Edited by Philip Yam

Bubbly Gone Flat

Water bubbles created by ultrasonic waves can collapse fast enough to generate a flash of light [see "Sonoluminescence: Sound into Light"; SciAm, February 1995]. In 2002 Rusi Taleyarkhan, then at Oak Ridge National Laboratory, claimed to have triggered nuclear fusion in these bubbles; in 2006 he published a second report of successful bubble fusion. In both cases, other researchers could not duplicate his work, and many were suspicious because he did not share his data. Contamination with a radioisotope could also explain his 2006 results.



FLASH POINT: In a flask of liquid, a bubble made by sonic waves can collapse to produce light.

The tempest over bubble fusion may have finally fizzled out. After their second investigation, officials at Purdue University, Taleyarkhan's current institution, charged him in July with two counts of misconduct after concluding that he falsely created the appearance that members of his lab had independently verified the sonofusion effect. (An earlier inquiry cleared Taleyarkhan, but lawmakers requested a more thorough investigation into the research, which received $318,000 in government funding.) Taleyarkhan has appealed the charges.

In 2007 Kenneth Suslick of the University of Illinois and Seth Putterman of the University of California, Los Angeles, reconstructed Taleyarkhan's original experiment but found no fusion. At this point, scientists have given up, Suslick says: "These experiments were deeply flawed at best and have had no credibility for several years." —*JR Minkel*

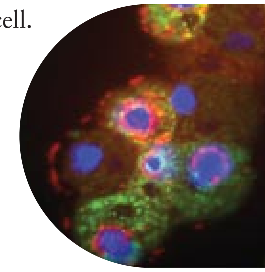
Family Guy

Lonesome George, the famous bachelor tortoise of the Galápagos, may soon be a father. The sole survivor of a population on Pinta, a northern island of the Galápagos—pirates and sailors had eaten the rest of his kind—George now lives at the Charles Darwin Research Station on Santa Cruz. In 1990 two females from Isabela Island joined him. Unfortunately, George showed little sexual interest or prowess. In July, however, one female produced nine eggs, three of which were undamaged and collected for incubation. Because turtles can lay unfertilized eggs, no one will know if George has sired offspring until mid-November, when the eggs should hatch if fertile. Success could mean the eventual restoration of the Pinta subspecies [see "On the Origins of Subspecies"; SciAm, March 1999].

It's Alive?

For decades scientists have argued about the life status of viruses [see "Are Viruses Alive?"; SciAm, December 2004]. Researchers at the University of the Mediterranean in Marseille, France, and their colleagues have discovered that viruses can fall ill through infection by other viruses. The finding, published online by *Nature* August 6, provides an indication that viruses could be considered living.

The researchers looked at the giant mamavirus, which is as large as a small bacterium, about 750 nanometers. Electron microscopy revealed a tiny virus about 50 nanometers across that is closely linked with the mamavirus. Lacking the ability to infect cells, the satellite virus, dubbed Sputnik, relies on mamavirus to do the job. Then Sputnik hijacks the replication factory that mamavirus has set up in the cell.



"SPUTNIK" virus (*green*) and mamavirus (*red*) proliferate next to nuclei (*blue*) of amoeba cells.

The result is more Sputnik and fewer and often deformed mamavirus. Genome studies suggest giant viruses and their "virophages" may be common in the oceans. —*Charles Q. Choi*

Light Work

Light-emitting diodes are making their way into everyday life [see "In Pursuit of the Ultimate Lamp"; SciAm, February 2001]. Still, LED versions of 60-watt incandescent bulbs can cost around $100. Engineers at Purdue University report a way to make cheaper blue LEDs, which are needed to generate white light. Conventionally, such LEDs require gallium nitride to be placed on a substrate of sapphire, with a separate reflector to direct the light. In the July 14 *Applied Physics Letters*, the researchers describe making LEDs on silicon with a built-in reflective layer, which reduces cost; with mass manufacturing, affordable LED lamps could appear in two years, they predict. ▪

DAVID J. FLANNIGAN AND KENNETH S. SUSLICK *University of Illinois* (*bubble*); FROM "THE VIROPHAGE AS A UNIQUE PARASITE OF THE GIANT MIMIVIRUS," BY BERNARD LA SCOLA ET AL., IN *NATURE*; PUBLISHED ONLINE AUGUST 6, 2008, REPRINTED BY PERMISSION FROM MACMILLAN PUBLISHERS LTD (*virus*); GUILLERMO GRANJA *Reuters* (*tortoise*)

NEWS SCAN

IN THIS ISSUE: Dead Zones ■ Glaciers ■ Soundscapes ■ Green Economics ■ Augmented Reality ■ Forest Danger ■ Aging

OCEANS

Suffocating Seas

Climate change may be sparking new and bigger "dead zones" BY BARBARA JUNCOSA

"Wasteland" conjures up visions of dusty desolation where life is fleeting and harsh—if it exists at all. Oceans, too, have their inhospitable pockets. Scientists are discovering that climate change—and not just fertilizer from farm use—may be spurring the emergence of barren underwater landscapes in coastal waters. Expanding dead zones not only spell trouble for biodiversity, but they also threaten the commercial fisheries of many nations.

Dead zones are not new; they form seasonally in economically vital ecoystems worldwide, including the Gulf of Mexico and Chesapeake Bay. Agricultural runoff sparks many of these die-offs; increased use of nitrogen fertilizers has doubled the number of lifeless pockets every decade since the 1960s, resulting in 405 dead zones now dotting coastlines globally.

But lesser-known wastelands are also emerging—without nutrient input from farms. Alarms about such dead zones first sounded in Oregon during the summer of 2002. Usually "we see many schools of fish and lots of different species," says David Fox of the Oregon Department of Fish and Wildlife, but surveys revealed dead fish and invertebrates littering the seafloor. The culprit was hypoxia—low-oxygen conditions, which can occur after the decomposition of organic matter in areas where deep waters well up to the surface.

The emergence of hypoxic areas so close to shore has startled researchers, comments Jack Barth, a physical oceanographer at Oregon State University. A decade ago scientists needed to sail out 50 miles or more to find hypoxic water off Oregon, but he says, the zone was now so close that "a long baseball homer hit off of highway 101" could land in it. To scientists' surprise and dismay, "hypoxia has become a feature of the coast," with its reemergence near shore every summer, states Francis Chan, a marine ecologist, also at Oregon State.

Ordinarily upwelling systems such as that off Oregon teem with life. As coastal winds push surface waters offshore, cold, nutrient-rich waters from below replace them, stimulating plankton blooms that serve as food for many marine organisms. In fact, upwelling systems lead to such productive ecosystems that they support some 20 percent of the world's fisheries' yield while making up just 1 percent of the ocean surface.

Dead zones can form, however, when these systems become supercharged, either because of fertilizer runoff or, as in the case of Oregon, because of changes in ocean circulation. When upwelling intensifies, more nutrients go to the surface, where plankton growth skyrockets. Those that are not eaten eventually die and rain down into deeper waters, where bacteria use available oxygen to decompose them. Hypoxia results when the rate of this widespread organic decay outpaces fresh supplies of oxygenated surface water.

Besides Oregon, other regions are seeing signs of enlarging dead zones. In South Africa, shifts in the upwelling ecosystem have been documented since the early 1990s. Recurring episodes of hypoxia along the coast have resulted in an increased frequency of commercially valuable rock lobsters traveling closer to shore in search of oxygenated waters, only to become stranded when the tide recedes. Along the coasts of

CAKED WITH CRABS: An intertidal pool in Cape Perpetua, Ore., collects Dungeness crabs that choked to death. Climate change seems to be starving some waters of oxygen.

COURTESY OF ELIZABETH GATES *Oregon State University*

Chile and Peru, where hypoxic episodes have taken place for thousands of years, changes may be brewing as reports of huge numbers of Humboldt squid and fish washing up on beaches after low-oxygen events have increased in recent decades. Prolonged hypoxia in these systems could precipitate "a drop in species diversity, with some groups, such as crustaceans, disappearing more quickly," says Lisa Levin, a marine ecologist at the Scripps Institution of Oceanography.

Andrew Bakun of the University of Miami thinks that global warming may be driving the changes in upwelling, an idea he first proposed in 1990. As continents heat up, the pressure difference between air over warmer landmasses and that over the cooler ocean increases, which could strengthen coastal winds that drive the upwelling process. Short periods of unusually strong winds, for example, preceded each hypoxic event in Oregon. Although long-term wind data have proved difficult to analyze, coastal winds in Chile and South Africa appear to have intensified in recent decades.

Climate models have also predicted large-scale declines in oceanic oxygen. As surface waters warm up, they become less efficient at absorbing oxygen and act as a cap, preventing the mixing of oxygen into deeper layers. If upwelled into coastal regions, these deep waters—depleted in oxygen but rich in nutrients—may prime local areas for hypoxia. Studies have documented a drop in oxygen levels across the Pacific Ocean, possibly contributing to the emergence of hypoxia in Oregon.

The primary challenge facing scientists is lack of sufficient long-term data for upwelling systems, states Jane Lubchenco, an Oregon State marine ecologist. A recent symposium highlighted the urgent need for more monitoring, as well as the importance of continued communication among scientists. "It is clear that these systems are not exactly alike," Lubchenco notes, but comparing them may help researchers figure out how hypoxia develops. Ultimately, predicting future changes will be crucial in determining if—or more likely, when—expanding low-oxygen zones might choke fisheries worldwide.

GLACIOLOGY

The New Ice Doctors

Researchers hone seismic skills to peer inside glaciers BY KRISTA WEST

Glaciers at the earth's poles are melting, calving and surging toward the seas at alarming speeds. With few exceptions, global glaciers have been getting smaller since the early 20th century, according to the National Snow and Ice Data Center in Boulder, Colo. The suspected cause of all this shrinkage, of course, is warming temperatures. The consequences are not surprising: a warmer world could mean melting ice, rising seas and flooded coastlines.

To learn more about what is happening, researchers in the bursting field of glacier seismology are refining techniques to track changes inside the ice in real time. Specifically, they are using seismic instruments to listen to ice movements, like physicians use heart rate monitors to learn about a patient's health. With such information, these ice doctors could better determine how glaciers are changing over short periods—a sharp contrast to more traditional methods in which glaciologists relied on photographs, satellite images and direct measurements to document large-scale, long-term ice movements.

Glacier seismology exploded onto the scene after 2003 with the surprise discovery of a new class of ice movements in Greenland by Columbia University's Göran Ekström and Meredith Nettles. The strong seismic signals were recorded across the globe; researchers suggested that they were caused by Greenland's glacial ice surging forward by as much as 10 meters in less than 60 seconds and that the late summer events had been increasing since at least 2000—clearly showing a link to large-scale climate change. Since then, scientists have watched other small-scale, short-term movements and features inside the ice: the opening of crevasses; calving at the glacier terminus; water surging underneath the ice and into cracks at the bottom; and friction points below the glacier.

ICE BREAK: **Seismic data enable scientists to peer inside melting glaciers before they calve.**

MARKUS RENNER *Getty Images*

Before scientists can use the data to predict ice behavior and climate change, they

still need to determine exactly how to interpret glacial seismic records accurately. For instance, what was initially identified in publications as an "ice quake" in Greenland now appears to be a different kind of ice movement. At the June workshop of the Incorporated Research Institutions for Seismology (IRIS) in Stevenson, Wash., Nettles suggested that the apparent ice quakes might not be surges at all but could actually be major ice-calving events.

When a glacier calves, huge pieces of ice—some approaching half a cubic kilometer in size—suddenly break off, transferring large masses of freshwater from land to sea and raising sea level instantly. According to a study in the August 24, 2007, issue of *Science,* melting and calving of glaciers (as opposed to icebergs or ice sheets) account for more than half of the ice lost to the sea since 1996. Shad O'Neel, a coauthor of the paper and a glaciologist with the U.S. Geological Survey in Anchorage, studies glacier-calving trends in Alaska with local seismic instruments. Here the leading edge of a glacier called Columbia has shrunk by about 16 to 18 kilometers because of calving in the past 25 years. At the same time, the glacier as a whole is surging forward. "The ice is moving faster in the forward direction but is calving even faster," O'Neel explains. "Sea-level rise is a really strong motivator" for understanding this glacier's movements, he adds.

At the southern tip of the world, glacial surges are on the examination table, too. By analyzing seismic records, Washington University seismologist Douglas Wiens and Pennsylvania State University glaciologist Sridhar Anandakrishnan discovered that the stick-slip surges of Antarctica's Whillans glacier happen twice a day with the tides and that the surges have been slowing down since at least 1994. One explanation, Anandakrishnan says, is that climate-induced sea-level rise is affecting movements of the ice.

Understanding the inner causes of glacial calving and surging could provide insight into how ice will respond to a warming world. These topics were highlighted at the June IRIS workshop, which held its very first session on glacial seismology, co-organized by Wiens; there Nettles, Anandakrishnan and many others presented their findings. The field is growing rapidly, Wiens remarks. Seismologists get a new place to apply their skills, glaciologists get a new tool to apply to the ice and everyone learns more about changing ice.

Krista West is a freelance writer based in Fairbanks, Alaska.

BIOACOUSTICS

Calls of the Wild

Tracking how human activity upsets natural symphonies BY MICHAEL TENNESEN

The eureka moment for Bernie Krause, a bioacoustics expert, came when he was on the Masai Mara National Reserve in Kenya recording the natural ambient sounds of birds, animals, insects, reptiles and amphibians for the California Academy of Sciences. As a former player of the Moog synthesizer for George Harrison, the Doors and other 1960s rock musicians, he had made a spectrograph of a natural soundscape and realized that "it looked like a musical score," he recalls. "Each animal had its own niche, its own acoustic territory, much like instruments in an orchestra."

How well these natural musicians played together, Krause concludes, says good deal about the health of the environment. He argues that many animals evolved to vocalize in available niches so they can be heard by mates and others of their kind, but noise from human activity—from airplanes flying overhead to rumbling tires on a nearby road—threatens an animal's reproductive success.

Since the late 1960s Krause has collected over 3,500 hours of soundscapes from Africa, Central America, the Amazon and the U.S. He finds at least 40 percent of those natural symphonies have become so radically altered that many members of those orchestras must be locally extinct. "Forests and wetlands have been logged or drained, the land paved over, and human noise included, making the soundscape unrecognizable," says Krause, who heads Wild Sanctuary in Glen Ellen, Calif., an archive of natural sounds. Lately he has traveled to Katmai National Park and the Arctic National Wildlife Refuge to look for unpolluted sound and still had to get away from roads to find it.

Thomas S. Schulenberg, a neotropical bird specialist at Cornell University and one of the authors of *The Birds of Peru,* agrees that sound is a useful tool for assessing the natural environment. Schulenberg traveled to Vilcabamba, a wilderness of wet cloud forest in eastern Peru, which Conservation International wanted to access for possible protection. Although the ornithologist carried a pair of binoculars, he showed up to their dawn chorus with a directional microphone and recorder. As Schulenberg puts it: "You can hear many times more birds than you can see."

Schulenberg believes animals can adapt to some noise pollution, but there are limits, especially if the noise becomes a permanent feature of the environment. Writing in the *Journal of Animal Ecology,* biologist Henrik Brumm of the Free University of Berlin found that male territorial nightingales in Berlin had to sing five times as loud in an area of heavy traffic. "Does that have effects on the musculature they need to sing?" Schulenberg wonders. "Can they sing even louder, or are they going to eventually hit a

wall and be washed out by human noise?"

The U.S. National Park Service, under its Natural Sounds Program, wrestles with similar questions. Karen K. Trevino, the program director, cites studies showing that when exposed to the sounds of planes and helicopters, bighorn sheep forage less efficiently, mountain goats flee and caribou do not successfully reproduce as frequently. Senior acoustic specialist Kurt Fristrup of the National Park Service notes that human sounds cause problems other than acute annoyances. Namely, they can "mask some of the quieter yet important sounds of nature like footfalls and breathing—the cues that predators listen for to catch prey and that prey use to escape predators," he says.

According to Krause, sound can also help determine how habitat destruction alters species populations. He did a 15-year study in Lincoln Meadow in the Sierra Nevada Mountains, a region that was selectively logged and of which loggers insisted there would be no change. Photographs showed little change, Krause found, but audio revealed a drastic drop in species diversity and density. Says Krause: "The transformation from a robust natural symphony to almost silent was quite alarming."

Michael Tennesen is a freelance writer based near Los Angeles.

Q&A WITH THOMAS L. FRIEDMAN

Green Pay Dirt

Why strategies to tackle climate change will boost the economy BY STEVE MIRSKY

Some politicians and pundits fear that addressing global warming will drain the U.S. economy and hurt the nation's competitive edge. But going green and clean is the best way to remain an economic powerhouse, argues Thomas L. Friedman in his new book *Hot, Flat, and Crowded: Why We Need a Green Revolution—and How It Can Renew America* (Farrar, Straus and Giroux, 2008). We asked Friedman, a *New York Times* op-ed columnist, to explain his thinking.

What do you mean by the title *Hot, Flat, and Crowded?*

It refers to the convergence of three big seismic events. The first is global warming. Second is what I call global flattening: the rise of middle classes all across the world that increasingly have the kind of energy and consumption patterns, demands and aspirations of Americans. Crowded refers to global population growth. These events are like three flames that have converged to create a really big fire, and this fire is boiling a whole set of problems.

You say that going green is a national security imperative and that green is the new red, white and blue. Can you explain that?

Clean power is going to be a source of power generally in the world—every bit as much as tanks, planes and nuclear missiles have been during the cold war. The country that takes the lead in clean power and clean tech is going to be an economic and strategic leader in the 21st century. If we take the lead in that industry, we will be generating the kind of innovation, competitiveness, respect, security and breakthroughs to help the world. In so doing, we will make ourselves more respected, stronger, more secure, entrepreneurial, richer and competitive.

You argue for an overhaul of our energy system. Why is such a drastic measure needed?

If you don't do things systematically, you end up doing corn ethanol in Iowa and thinking you solved the problem, when all you have done is drive up food prices and encourage more people to plant, say, palm oil in the Amazon. Right now we have a system. It is the dirty-fuel system. One mile from your house, you can probably find a gas station....

One block, actually.

Exactly, so this system works really well, and it gets that dirty fuel from the oil well to the tanker to the refinery to your neighborhood and into your car. Of course, we now know in doing that we are also de-

GLOWIMAGES/GETTY IMAGES

HOT AND CROWDED: **In terms of economics, the problems of booming populations and rising living standards on a warmer earth may best be handled with green energy technologies.**

spoiling the environment, strengthening petro dictatorships, driving biodiversity loss, et cetera. We have to replace that system with a clean-fuel system.

So what will we need to start changing the system?

Innovative breakthroughs that we just do not have right now. What we don't have in energy today is a real market that would encourage 100,000 Manhattan Projects in 100,000 garages with 100,000 ideas.

How do you get to a market that rewards innovation?

You've got to shape it in two ways. One is with the right price signal. We have to have a tax on carbon that is long-term, fixed and durable. So those 100,000 inventors know if they do come up with that breakthrough, that if OPEC lowers the price of oil, it won't knock them out of the game. And the second thing is to rewrite the rules around our utilities, as people started to do in California and Idaho. Specifically, the utilities have to be paid not for kilowatts sold but for watts saved.

But how could a politician running for election sell a new gas tax?

So let's imagine you are in a campaign. Let's imagine the discussion, and your opponent says, "There goes my opponent, Mr. Friedman. Another tax-and-spend liberal; now he's for an energy tax. He's never met a tax he didn't like; now he wants to tax your gasoline more." What I would say is, "Let's get one thing straight. My opponent and I, we're *both* for a tax. I just prefer my taxes should go to the U.S. Treasury, and he does not mind that his taxes go to the Saudi, Russian or Venezuelan treasuries. Let's not fool ourselves that we're not paying a tax here [with our existing energy system]." If you can't win that debate, you don't belong in politics.

So what can the average citizen do to help alleviate the problems brought on by a hot, flat and crowded planet?

My mantra has been, "Change your leaders, not your lightbulbs," because leaders write the rules. The rules shape the market. The markets give you innovation at a speed, scope and scale that we need.

A podcast of the complete interview with Friedman, as well as the full transcript, is available at **www.SciAm.com/oct2008**

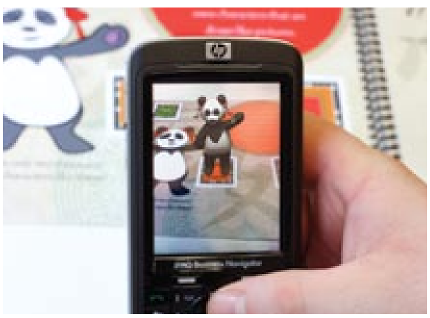
COMPUTING

Annotating the Real World

Augmented reality starts making commercial headway BY STEVEN ASHLEY

Rich Jenkins opens a child's picture book and aims a camera phone at a page depicting a cartoon panda bear that is gesturing toward a set of Chinese characters. As Jenkins and I view the page through the cell phone screen, the printed panda suddenly erupts into a 3-D video version that points at the first symbol, pronounces it in Mandarin and then defines it in English.

Jenkins, who leads Media Power, a New York City–based firm that develops mobile communications applications, smiles at my rather startled reaction. "A software application that we've downloaded into this phone reads cues that the book designers have embedded into the graphics," he explains. "It then calls up the video segment appropriate for that page from the network server. The result is like a pop-up book on steroids." Jenkins notes that this new kind of animated content could help kids learn and that these "magic books" could become available by the end of this year. The company will also be introducing cell phone–enabled museum exhibit tours based on the same technology, as well as the means by which consumers can trigger delivery of targeted advertising by directing camera phones at brand logos.



"MAGIC BOOK" PAGE triggers a video segment when viewed through a camera phone.

COURTESY OF MEDIA POWER, INC.

Media Power is part of a vanguard of organizations that is working to commercialize augmented-reality (AR) technology, which can be characterized as the timely overlay of useful virtual information onto the real world. According to Mark Billinghurst, director of the Human Interface Technology Laboratory at the University of Canterbury in New Zealand, AR incorporates three key features: virtual information that is tightly registered, or aligned, with the real world; the ability to deliver information and interactivity in real time; and seamless mixing of real-world and virtual information.

When explaining AR technology, Blair MacIntyre, who directs the Augmented Environments Laboratory at the Georgia Institute of Technology, often invokes the virtual first-down marker seen as a yellow stripe in televised football games. "The technical challenge of AR is to do something similar but more complex with the live video feed from a cell phone camera and without the 10-second delay required to generate the virtual marker."

Although AR has mostly lived in the lab (except, notably, in the form of head-up

displays for fighter jets), the recent emergence of highly capable mobile devices is fueling a surge in interest. (Much of the AR technology on cell phones is based on work done at Graz University of Technology in Austria.) "I think that we're on the cusp of widespread application of AR technology, perhaps in a year or two," Billinghurst says, pointing to the Eye of Judgment, a video game for Sony's PlayStation 3, as the most prominent example of the trend. Players look at cards through a camera and watch animated versions of the game characters on the cards fight one another. The ability is based on identifying real-world objects and estimating their locations in space.

AR-like technology is also finding its way into industrial manufacturing. InterSense, a Bedford, Mass.–based company, offers process-verification systems that use sensors and cameras to track the positions and motions of tools as workers do their jobs. Computers then compare the actual tool movements with ideal procedures to detect errors or confirm correct completion, information that is then provided graphically to the workers in real time.

If today's trends hold true, more AR-based products will arrive before long. Commercial entities that have entered the field are split among suppliers of AR-authoring and development tools, including ARToolWorks in Seattle, Germany's Metaio and France's Total Immersion, and large companies such as Sony, Canon, Qualcomm, Motorola and Nokia. Billinghurst estimates that around 40 academic labs shell out a combined $50 million to $60 million every year on AR research and that commercial firms spend two to three times that. Progress in AR depends on advances in display technologies ("virtual" eyeglasses, for example), tracking systems, cameras, and processors and graphics chips for mobile devices, as well as the means to deliver AR services wirelessly where and when users need them.

Widespread use of AR, though, will probably depend on integrating AR with social networking, Billinghurst states. Such a mix, he says, would, for example, "allow users to leave annotation notes—advice or opinions—for their friends on the network at sites such as restaurants or scenic spots all over the world." Reality would take on a whole new meaning.

The Road Better Traveled

Researchers at General Motors (GM) are developing a windshield that combines lasers, infrared sensors and cameras to monitor what is happening on the road ahead and deliver that information in a way that allows drivers to see their way a little more clearly. GM's prototype head-up display windshield will make objects ahead stand out, especially for aging eyes. The technology will enhance just a few objects that are already in a driver's view and avoid splashy, distracting data on the glass. When a driver was in heavy fog, for example, a laser would project a blue line onto the windshield that followed the edge of the upcoming road. Or if infrared sensors detected an animal in the driver's path during a night ride, the system would display its outline on the windscreen.

FIELD NOTES

Danger in the Forest

Drug traffickers and other outlaws confront scientists in a reserve BY CHARLES Q. CHOI

SMOKED: Settlers try to clear trees with fire in Guatemala's Maya Biosphere Reserve to make way for illicit cattle ranching. These and other illegal activities hamper conservation efforts.

COURTESY OF WILDLIFE CONSERVATION SOCIETY

Deep in the Maya Biosphere Reserve in Guatemala, armed men near a stopped white truck face us—one gripping a shotgun, another slashing a nearby branch with a machete. They glare at us menacingly as we drive by. "That was a perfect place to kill someone," half jokes our guide, Javier.

"Let's not talk about that right now," curtly replies Seth Factor, Guatemala director of the environmental advocacy group Trópico Verde. Bands of armed outlaws are a common threat in the western third of the Maya Biosphere Reserve—"the Wild West," as one scientist here has called it.

The reserve is the heart of the biggest intact forest in the Americas north of the Amazon—at 2.1 million hectares, it is roughly twice the size of Jamaica and covers nearly a fifth of Guatemala. In terms of biology, it is one of the richest forests in the world, boasting at least 100 mammal species, 400 bird species and 3,000 plant species. And it is also home to the epicenter of the ancient Maya civilization, holding the largest excavated Maya city, Tikal.

Fieldwork in this steaming-hot forest

has always been challenging; scientists must brave venomous snakes, flesh-burrowing botflies and repeated bouts of malaria. But in the past decade the risks have escalated as criminal activity has invaded the reserve's western region. Cocaine smugglers have burned tracts of forest to set up dozens of airstrips as way stations from the coca fields of Colombia to dealers in the U.S. Illegal squatters armed with assault rifles have kidnapped scientists and local officials. Poachers and loggers have beaten and shot police, soldiers and park rangers. Nearly everyone I approach is wary of speaking with me because of very real fears of political repercussions or criminal retaliation.

Efforts to drive back these outlaws are underfunded. "We are trying to control 20 percent of the country with less than 0.5 percent of Guatemala's national budget," explains Victor Hugo Ramos of Guatemala's national park service. The country's booming population may also speed the invasion of the forest—in Petén, the northern third of the country where the reserve lies, official estimates state that the population exploded from 25,000 in 1960 to 500,000 in 2004. The current numbers might actually approach one million, says Roan McNab, the program director in Guatemala for the Wildlife Conservation Society (WCS).

As we drove into Laguna del Tigre, the largest of the five national parks in the reserve, illegal ranches lined each side of the road. Although I could see the scorched forest attempting to recover from all the burning, the repeated use of fire has worn it down. Squatters have been selling land in Laguna del Tigre, even though they do not own it. "They are betting the government will let them stay there," Ramos says.

The scientists are now struggling to keep invaders from spreading eastward by patrolling a 45-kilometer-long firebreak between the ancient Maya sites of La Corona and El Perú-Waka' with the aid of Guatemalan authorities, a strategy that McNab dubs "the shield." "We've been able to hold the shield for the past five years under massive pressure from the invaders," he says. Volunteer pilots also run flights for the WCS to pinpoint fires and airstrips, and scientists relay that data to law enforcement.

There are more signs of hope from Guatemala's new administration. The country's president is taking an active interest in the area, and the park service has begun evicting squatters from the reserve, Factor explains. "But it's key not to focus on the impoverished communities that are driven by necessity—it's vital to target the large landholders."

As I interview McNab in his office in Flores, the capital of Petén, he is preparing to enter the field unarmed in spite of the danger, as he always does. He explains that he has managed to talk his way out of risky situations so far, and by going in armed, he could be seen as a threat. In the end, he adds, "I would rather die with binoculars in my hand than carry around a gun for the rest of my life."

He returned safe eight days later.

Charles Q. Choi is a frequent contributor based in New York City.

Protection for Guatemala's Species

Although poaching, squatting and drug trafficking make the situation in the western part of the Maya Biosphere Reserve grim, much of the rest of the reserve remains protected. There conservationists lure jaguars (*below*) to automatic cameras with the musky scent of Calvin Klein's Obsession. They also build predator-proof nests for the endangered scarlet macaw, track white-lipped peccaries with radio collars, and monitor legal, sustainable harvests of mahogany and cedar. "We have a living laboratory here of how nature can rebound after all the changes it must have experienced with the ancient Maya civilization," says Roan McNab of the Wildlife Conservation Society.

The future of the reserve may be in tourism, suggests archaeologist David Freidel of Washington University in St. Louis, who is excavating a Maya crossroads at El Perú-Waka'. "Tourism could genuinely be a source of major income, the way that it is in Maya areas of Mexico, and for that to happen, you're going to need a peaceful Petén," he says. Archaeologist Richard Hansen of Idaho State University and others are now working in the reserve to transform one of the largest Maya sites known, El Mirador, into a global attraction.

COURTESY OF WCS

BIOLOGY

Rethinking the Wrinkling

Key genes, rather than cell and DNA damage, as causes of aging BY MELINDA WENNER

It afflicts every creature on this planet, and everyone dreams of an antidote. But even after decades of research, aging largely remains a mystery. Now new research findings suggest there is a good reason for this impasse: scientists may have been thinking about the causes of aging all wrong. Instead of being the result of an accumulation of genetic and cellular damage, new evidence suggests that aging may occur when genetic programs for development go awry.

The idea that stress and reactive forms of oxygen—"free radicals" that are the normal by-products of metabolism—cause aging has dominated the field for 50 years. Studies on the worm *Caenorhabditis elegans* have shown that reducing exposure to reactive oxygen species increases life span, and worms that have been bred to live longer are also more resistant to stress. But few studies have definitively linked oxidative damage to altered cellular function.

Scientists have also noticed that intrinsic genetic changes accompany aging. As mice age, a gene called *p16INK4a,* which controls cell growth and regeneration, becomes more active in most tissues, preventing the cells from regenerating as easily as younger cells do in response to injury or disease. And compared with muscle stem cells in young mice, those in older mice accumulate a complex of proteins that, over time, transform muscle into fibrous, fatty tissue.

These findings did little, however, to challenge the idea that aging is the result of damage accumulation, because these genetic changes may simply be a consequence of aging rather than the culprit. "That's always the challenge, to try to get cause and effect," says Brian Kennedy, a biochemist at the University of Washington. And although studies have shown that changing the expression of certain genes can affect an organism's life span, it is unclear whether these genes are actually involved in the normal aging process.

A recent paper published in the journal *Cell,* however, suggests that genetic programs do drive aging. Scientists at Stanford University and the University of Colorado at Boulder compared the genes that turn on in young nematode worms with those expressed in old worms. Although more than 1,000 genes differed, most of them were under the control of just three, called ELT-3, ELT-5 and ELT-6. These genes are transcription factors—molecular switches that turn other genes on and off. "There were hundreds of things that had gone awry, but they were all traced back to these three transcription factors," which are known to be involved in the development of specialized membranous cells, explains Stanford developmental biologist and study co-author Stuart Kim. The expression of the three transcription factors also differed in young and old worms.

To see whether damage accumulation ultimately affected these transcription factors, the scientists exposed worms to oxidative stress, infection and radiation, but nothing affected the factors' expression.

GROWING OLD may not necessarily result from stress and oxidative damage to cells and DNA, as long thought.

The changes "seem to be intrinsic to the genome of the worm," Kim says—not brought on by outside influences. In addition, when the researchers stopped the expression of ELT-5 and ELT-6, which typically become more active in old age, the worms lived 50 percent longer. "I was totally surprised," Kim remarks.

The study's findings also agree with conventional wisdom linking life span to reduced calorie intake. The researchers found that the three transcription factors are under the control of the insulinlike signaling pathway, which controls how an organism's metabolism changes in response to famine. One of the things the insulinlike signaling pathway does during periods of caloric restriction, Kim says, is to reset the ELT transcription factors and their counterparts in other organisms "to a younger state." Scientists believe that the plant compound resveratrol, which increases life span in some organisms, mimics the effects of caloric restriction and resets these pathways, too.

Kim does not believe that the transcription factors are programmed to trigger aging. Instead, he speculates, their function becomes unbalanced as worms get older. Evolution, after all, selects for genes that help individuals reproduce, but once organisms have passed breeding age, they are no longer subject to its control. "Entire biological systems drift away when nature doesn't care anymore," Kim notes. ELT-3, ELT-5 and ELT-6 may play an important role in the development of young worms, but after their job is done, their function could go awry—and this "developmental drift," as Kim calls it, could actually cause aging.

The study does not prove that aging in worms is driven only by developmental drift, Kennedy observes. Both damage accumulation and drift could play a role, and other genetic circuits could also be involved. But the paper certainly gives scientists "something else to think about with regards to what might be driving the aging process," he points out. "It brings to the forefront a new hypothesis that can be tested in more detail."

What could these findings mean for people? If aging is primarily a genetic process, conceivably it could one day be preventable. No one yet knows, however, whether the human counterparts to the ELT genes—called GATA transcription factors—might also be involved in normal aging, but it is a question Kim and his colleagues hope to address soon. "We know how human development works," Kim says. "Now we just have to find out which of these pathways are not working as well in old humans."

Melinda Wenner is based in New York City.

FRANK SCHWERE *Getty Images*

MATERIALS

Scale Model for Armor

A living fossil could inspire tomorrow's armor. Engineers at the Massachusetts Institute of Technology, funded by the U.S. Army, investigated the primitive fish *Polypterus senegalus,* nicknamed the "dinosaur eel" for the suit of armor it sports. In experiments mimicking bites from a predator, the researchers found that each scale is made of three layers on a bone support that all complement one another to defy penetration. The outer coat is the hardest and most resistant to sharp teeth. The middle is softer and dissipates energy by deforming. The last layer has a plywoodlike structure, which prevents cracks from spreading. The precise sequence of these layers critically preserves armor strength—for instance, replacing the outer and middle layers in simulations increased risk of the scale coming apart. These findings, posted online July 27 by *Nature Materials,* could illuminate how fish evolved and lead to more effective ways of designing armor. —*Charles Q. Choi*

FISHY SHIELD: The "dinosaur eel" may hold the secret to future body armor.

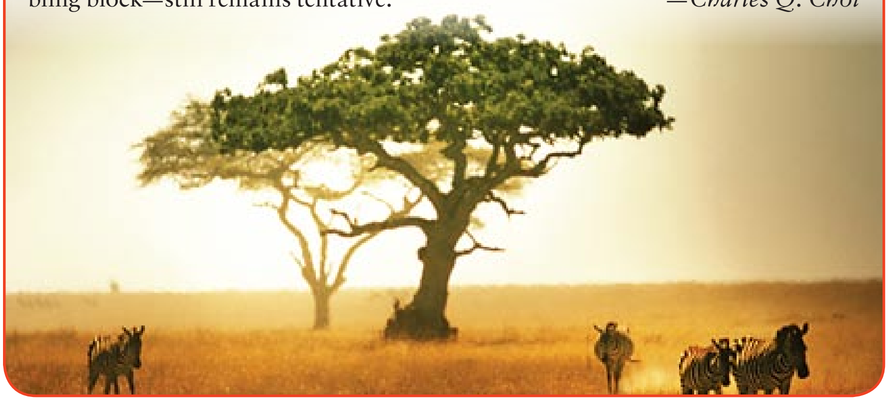
ENVIRONMENT

Making a Stand

Three years ago northern and central African nations that form the Community of Sahel-Saharan States agreed to a continent-wide belt of trees to combat the remorseless spread of the Sahara Desert. This past June they laid the groundwork for the Great Green Wall of Africa by formally adopting a two-year, $3-million initial phase for the project.

Green barriers against the Sahara have been around since the 1960s, but most have been small in scale. In contrast, the Great Green Wall will be 15 kilometers wide and will involve stretches of trees from Mauritania in the west to Djibouti in the east—a distance of some 7,000 kilometers. The aim is to protect the Sahel Belt—the dry savanna south of the Sahara—and prevent its precious arable land from desertification. The trees would also provide a source of firewood, crops and jobs. Projects to water these trees—say, by harvesting rain—could also help communities irrigate their fields all year long or even help them raise fish.

Pilot planting efforts, using local trees such as acacia (*below*), were scheduled to have begun in September. Funding for the entire project—perhaps its main stumbling block—still remains tentative. —*Charles Q. Choi*



COURTESY OF DONNA COVENEY *Massachusetts Institute of Technology (fish)*; TOMEK SIKORA *Getty Images (acacia tree)*; ILLUSTRATION BY MATT COLLINS

Data Points

Smoke-Free Funds

Philanthropists Bill Gates and Michael Bloomberg, New York City's mayor, announced in July a $500-million commitment to fight global tobacco use, especially in developing nations, where the burden of addiction is more costly. The money will support tobacco-control efforts, such as increasing cigarette taxes, modifying tobacco's advertising image and helping people quit.

Number of tobacco users worldwide: **1 billion**

Number in China: **350 million**

Annual number of deaths worldwide: **5 million**

Average number of years of life lost by a smoker: **15**

Percent of tobacco-related deaths by 2030 that will be in low- and middle-income countries (for which tobacco data are available): **80**

Population of these countries: **3.8 billion**

Amount collected by these countries in annual tobacco taxes: **$66.5 billion**

Amount they spend on tobacco control: **$14 million**

SOURCES: Bill and Melinda Gates Foundation; World Health Organization

In Brief

PLURIPOTENT CELLS MOTOR ON

Researchers have used genes to make adult cells pluripotent, that is, capable of giving rise to any cell type. But whether the reprogrammed cells could then generate specific cells needed to treat a disease was uncertain. Scientists at Harvard University and their colleagues have succeeded in making pluripotent the skin cells from an elderly patient with Lou Gehrig's disease (amyotrophic lateral sclerosis). Exposed to the right molecules, the induced pluripotent stem cells turned into motor neurons, which the ailment normally destroys. *Science* published the finding online July 31. *—Charles Q. Choi*

ANCHORS AWAY FOR REEFS

A new study confirms that coral reefs will face tough conditions from rising greenhouse gas levels. The reason: marine cements that bind together and anchor reefs cannot form in water full of dissolved carbon dioxide (CO_2). Researchers report in the July 29 *Proceedings of the National Academy of Sciences USA* that naturally acidic water in the Pacific Ocean off Central America keeps local reefs soft—a preview of how coral reefs may fare worldwide as atmospheric CO_2 levels rise. *—David Biello*

EXERCISE PILL

A drug might someday turn you into a long-running machine without a day of exercise. It might work, in essence, by reprogramming sugar-burning, fast-twitch muscle into fat-burning, slow-twitch muscle that does not tire as easily. The key to this transformation is a protein called PPAR-delta, which had been shown to create so-called high-endurance marathon mice if the animals were genetically engineered to make a lot of it. Besides supercharging stamina, the drug, called AICAR, might also treat muscular dystrophy as well as metabolic diseases such as diabetes, because it appears to help the body use and remove glucose from the blood more effectively. *—Nikhil Swaminathan*

MARS

No Ruling Out Life

PERCHLORATE, a microbial food, was detected in this trench.

The Mars Phoenix lander discovered evidence of perchlorate (ClO_4) and water ice in Martian soil, NASA researchers announced in August. Perchlorate, a highly reactive chemical that can occur naturally in arid areas such as Chile's Atacama Desert, was detected in two soil samples analyzed by Phoenix's wet-chemistry laboratory. Considered harmful to fetuses, perchlorate provides fuel for some microbes. For that reason, the discovery says little by itself about the possibility of life on Mars, NASA scientists say. Water ice was also identified in chunks of soil vaporized by Phoenix's gas-analyzing instrument. The result confirms 2002 observations by the Mars Odyssey orbiter, which detected ice in the form of subsurface hydrogen atoms at the planet's poles. In light of these successes, the space agency extended the Phoenix mission by five weeks, to September 30. *—JR Minkel*

HIV/AIDS

Infection Correction

Keeping tabs on the HIV/AIDS epidemic is crucial for formulating treatment and prevention strategies, but the U.S. has greatly underestimated the annual number of new infections. An assay that differentiates between recent and long-standing infections has led scientists to conclude that 56,300 individuals in the U.S. contracted the virus in 2006; previous annual estimates had it at 40,000. African-Americans (83.7 infections per 100,000) and Hispanics (29.3 per 100,000) continue to be disproportionately affected compared with whites (11.5 per 100,000). The results, in the August 6 *Journal of the American Medical Association*, follow disappointing news about HIV vaccines, including the cancellation of a large trial called PAVE 100. *—Philip Yam*

OPTICS

Microscope on a Dime

A lensless microscope the size of a dime might quickly and cheaply scan blood for tumor cells and parasites. In the device created by Changhuei Yang and his team at the California Institute of Technology, light shines on a liquid sample flowing through a narrow channel, below which are one-micron-wide apertures spaced 10 microns apart.

COIN-SIZE MICROSCOPE works without lenses, using digital camera–like sensors instead.

The light shines through the holes onto a semiconductor chip studded with sensor pixels similar to those in digital cameras. Objects that float over the apertures block some of the incoming light received by the pixels, which construct an image of the object based on the variations in light intensity. Details down to 0.8 to 0.9 micron are apparent. (Cancer cells typically measure 15 to 30 microns.) With a chip-based microscope, "there's no lens to break," says Yang, who was inspired by "floaters," the clumps of dead cells and other debris in the eye. Better yet, they cost about $10 a pop. *—JR Minkel*

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COURTESY OF NASA/JPL-CALTECH/UNIVERSITY OF ARIZONA/TEXAS A&M UNIVERSITY (*Mars*); JEFF FOOTT *Getty Images* (*coral reef*); COURTESY OF CHANGHUEI YANG *California Institute of Technology* (*dime and microscope*)

Galicia
Living Knowing

Universidade Galega

XUNTA DE GALICIA

Your Gateway to Europe

Laura Sánchez Piñón
Regional Minister of Education and Universities of the Government of Galicia
www.xunta.es

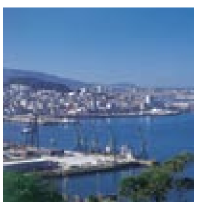
Galicia is always willing to go that extra mile, like any university graduate looking for the ideal location in which to undertake a postgraduate program. A master's or doctorate course can afford the further training and specialization that today are so essential for bright career prospects, but it is important to choose wisely when deciding where to take it.

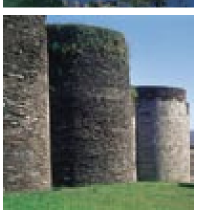
These pages explain some of the reasons why the universities of Galicia are an excellent choice. Alongside their commitment to quality, their high academic standards and the opportunities they provide for research and for finding employment, Galicia's universities offer the advantages of the region's role as a gateway to Europe. This is so not only in the geographical sense, but also as regards the opportunities it offers its students to round out their training at other centers throughout the continent.

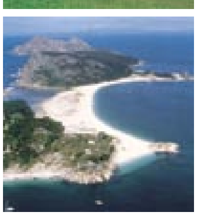
All together, Galician universities offer 102 master's and doctorate courses adapted to the requirements of the new European Space for Higher Education, in which the dissolution of borders means that to study in Galicia is now, more than ever before, to acquire a European education.

With the experience gained over 500 years at the University of Santiago de Compostela, coupled with the youth and drive of the Universities of A Coruña and Vigo, Galicia offers its university students an educational model that meets the demands of the international labor market and sustains the commitment to a knowledge-based economy of a region in continuous development: public universities that are innovative and competitive, welcoming graduates into a culture of excellence and social engagement to wellbeing, sustainability, economic growth, and cultural development.

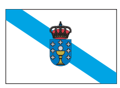
And I would add that in Galicia a first-rate academic experience is always accompanied by a lifestyle experience that is really worthwhile. Our ancient culture and wealth of wildlife and other natural beauties are unique in Europe, and make for the best of all possible starts to any learning circuit on the Old Continent.







What is Galicia
It is a region located in the Northwest of Spain



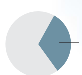
Where is it
In the world

In Europe

Population **2,772,533**
Surface area **29,574 km²**
Capital **Santiago de Compostela**

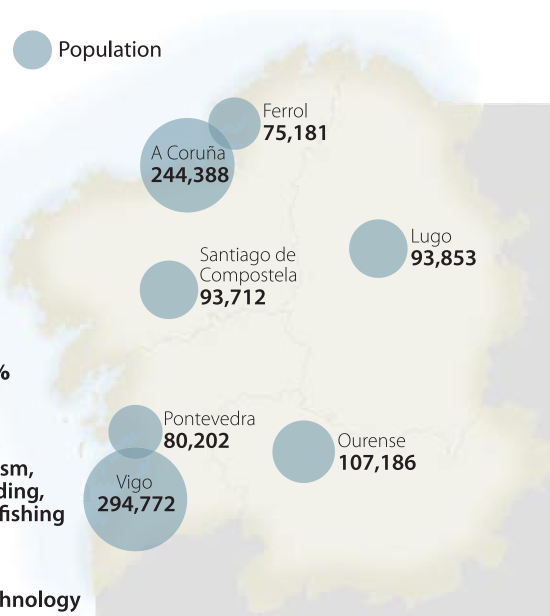
Life expectancy
84 years **76.8 years**

Active population with university education



Main production industries
Automotive, clothing, tourism, transport, energy, shipbuilding, wood, granite, agriculture, fishing

Expanding industries
Information technologies, renewable energies, biotechnology



Innovation in Galicia:
Universities Set the Pace for Development

Galicia is a rapidly developing region that is integrated in the knowledge economy and the culture of innovation. It is one of the fastest-growing regions in Spain, ranking among the top four in 2007, with an increase in per capita income one percentage point higher than the European average.

Its universities – University of Santiago, University of A Coruña and University of Vigo – are crucial to this progress. Their driving role is seen in their weight among the indicators used to monitor an advanced economy. In the past decade, the percentage of the Galician gross domestic product devoted to university R&D has doubled, the number of full-time university-based researchers has tripled, and one in three employed persons has a university degree. In short, the figures show that the vigor of the Galician economy is closely linked to that of its universities, which contribute to the region's leading position in various fields through their social integration, their value for job placement, and their predominant contribution to the innovation system.

The scientific and technological leadership of Galician universities is reinforced by an international profile that is particularly evident in their postgraduate study programs. The high academic and scientific standards of European university education and research are manifest in the master's and PhD programs offered in professional and scientific areas, ranging from Biotechnology to Cultural Services, or from Energy Sustainability to Mathematical Engineering.

Galician universities likewise match their European competitors as regards the scope and vitality of the research they engage in, and have attracted the involvement of institutions of global relevance such as the Bill and Melinda Gates Foundation, the European Space Agency, the World Health Organization, and UNESCO, which all provide funding for projects of economic and social impact pursued by international scientific consortia led by Galician researchers.

The interaction of its university departments with the international scientific community leads to intellectuals and scientists of worldwide reknown being a familiar sight on Galician university campuses. In recent years, up-and-coming researchers and university students have been able to learn from the experience of intellectuals such as Hans Küng or Paul Ricoer, and scientists such as the Nobel Prize winners Chen Ning Yang, David Gross, Frank Wilczek, John Nash or John Walker.

The universities

Universidade da Coruña

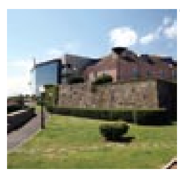
A Coruña campus – Ferrol Campus

Students **More than 23,000**

Lecturers **1,400**

Visiting students **323**

Students in other universities **245**



Universidade de Santiago de Compostela

Santiago de Compostela campus – Lugo campus

Students **More than 32,000**

Lecturers **2,200**

Visiting students **798**

Students in other universities **540**

Universidade de Vigo

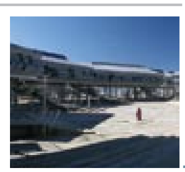
Vigo campus – Pontevedra campus – Ourense campus

Students **More than 23,400**

Lecturers **1,900**

Visiting students **426**

Students in other universities **433**

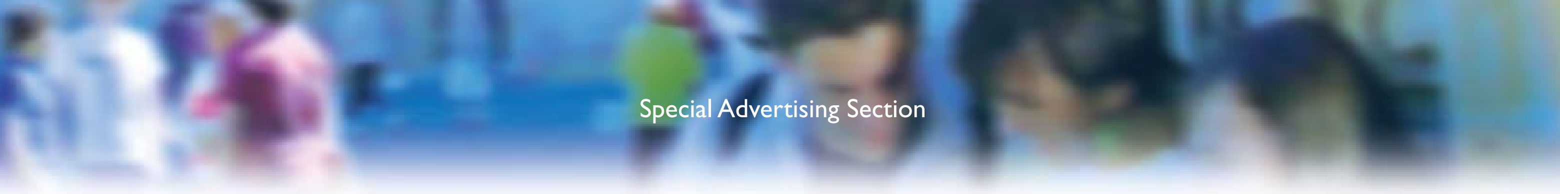


- University students registered in Galicia **71,679**
- University lecturers **5,489**
- Researchers working at the university **6,343**
- Doctoral students trained each year **6,000** **(with a sustained 4% annual increase this decade)**
- Total annual expenditure of universities **$680.5 million**

R&D&i in Galicia

In 2006

- Total expenditure on innovation in Galicia **$1.299 billion**
- Staff dedicated to R&D activities **8,280**
- Annual expenditure on R&D per researcher **$135,618**



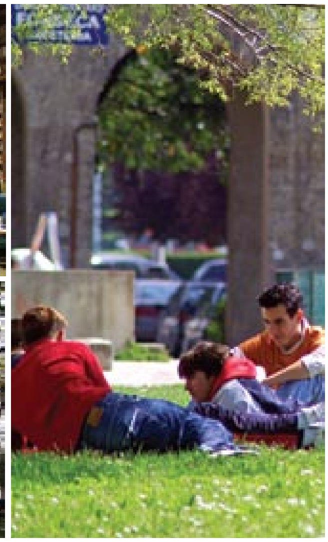
The Universities of Galicia:

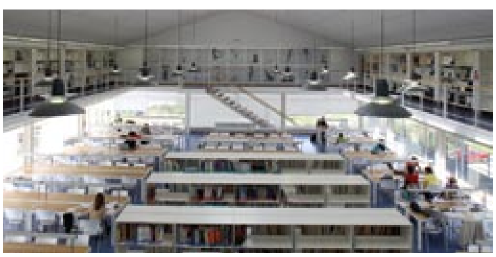
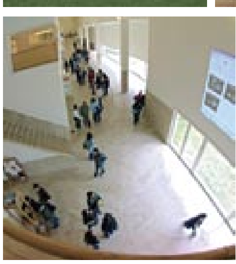
Organized around seven complementary campuses that embrace all areas of knowledge, and with noteworthy research capacity and technological facilities, the University System of Galicia (SUG) is a public higher education structure that pursues both the advancement of its undergraduate and postgraduate students, and the social and economic progress of the region.

Past and future join forces in Galicia's three public universities to rank them amongst the most prestigious in Spain, not only as regards the learning opportunities they provide, but also for the research they produce, which appears in the leading international scientific journals, and for their capacity to interact with the most diverse industrial and economic sectors.

The universities of Galicia, which are integrated in the European Space for Higher Education, offer 177 official first degree programs characterized by their academic quality and the syntony between their content and the social and professional needs of the European Union. The 73,000-odd undergraduate students and almost 6,000 postgraduate students who pursue their studies on its seven campuses have at their disposal a comprehensive range of halls of residence, cultural and sports facilities, and a modern network of libraries conceived as resource centers for teaching, research, study, and learning.

With their dynamic, competitive atmosphere, and infrastructures and facilities comparable with those of the best of European research centers, Galician universities are also a splendid choice for scientists looking to orient and develop their careers at the highest level, as is testified to by their annual output of more than 400 PhDs. And in addition to the academic and career opportunities they offer, Galicia's three universities enjoy many other advantages that make them especially attractive to undergraduate and post-


graduate students, academics, and researchers. Their teaching and research centers are set in a social and physical environment that combines quality of life, excellent communications, and all the history and culture of one of Europe's best-preserved regions; and foreign students and researchers are welcomed and attended to by specialized staff who advise and support them during their integration in these friendly academic institutions steeped in tradition.

The wide range of first degree courses is echoed by the doctorate and master's degree programs on offer. In general, the distribution of these programs among the three universities tends to reflect the particular academic and scientific strengths and focus of each. Thus at this level the University of Santiago de Compostela (USC) concentrates principally on health sciences, law, social sciences, arts, natural sciences and mathematics; the University of Vigo centers on electronic engineering, communications, marine science, energy, food technology, and economics; and the University of A Coruña focuses on areas such as civil engineering, architecture, industrial engineering, information technology, computer science, electronics and systems, and natural resources.

With its 673 research units, the SUG is the scientific motor of Galicia, and has played a fundamental part in the modernization that this region of Spain has undergone in recent years. During this time it has also evolved itself, striking a balance between the pursuit of pure science and the generation of wealth and well-being in the society it serves. On its seven campuses, more than 8,000 people work on an average of about 700 R&D projects with public or private funding.

Academic Tradition and Scientific Innovation

Within the broad spectrum of this postgraduate training and research effort, certain areas of activity stand out for their capacity to connect with industry and with society in general, or for the international recognition afforded to them.

In Santiago de Compostela, for example, a large part of USC's human, physical and financial resources, including almost 1,000 scientists, are involved in biomedical and pharmaceutical research projects combining expertise in medicine, pharmacy, chemistry, biology and physics; in collaboration with medical and research workers at the University Hospital Complex of Santiago de Compostela (www.chusantiago.sergas.es), this "bio-pharma-med" constellation is one of Spain's leaders in experimental research in the health sciences. With its capacity to attract significant investment and enter into consortia at the highest international level, it also attracts top-ranking researchers eager to apply their biotechnological, pharmacochemical and biomedical talents to the elucidation of disease mechanisms, the identification of therapeutic targets, and the design and synthesis of novel drugs.

Research in the biomedical and pharmaceutical field is also carried out at the Universities of A Coruña (www.canalejo.org) and Vigo (www.fichuvi.org), which with the collaboration of their local Hospital specialize in the development of innovative processes in the fields of rehabilitation, gerontology, and thermotherapy – these centers award degree qualifications in areas such as physiotherapy, chiropody, and occupational therapy – and in clinical areas such as cardiology and neuroscience.

Furthermore, it is the *raison d'être* of a number of new research centers that have been created with a view to the achievement of economic impact through transfer of the knowledge generated by their scientific excellence. With their state-of-the-art systems for work in genomics, proteomics, nanobiotechnology, drug delivery and high-throughput screening, backed up by up-to-date facilities for NMR spectroscopy, x-ray diffractometry, mass spectrometry and other techniques, these are among Spain's best-equipped research centers.

Another field in which work of international importance is done in Galicia is high-energy physics. The institute of this name not only collaborates with the European Organization for Nuclear Research (CERN) – it is currently taking part in two Large Hadron Collider experiments – and contributes to the German FAIR accelerator project, but is also active in the areas of medical physics and grid computing technology.

Galician universities, with the support of the Supercomputation Center (CESGA), carry out reference research in scientific disciplines such as mathematics or computer sciences, particularly in fields such as computational calculus and mathematical modelization. Indeed, CESGA (www.cesga.es) houses the Finis Terrae supercomputer, which has one of the biggest memories in Europe. Since it was put into operation on April 1, 2008, it has collaborated on solving more than 20,000 scientific calculus tasks in areas such as meteorology, industrial modelization, nanobiomedicine, medical chemistry and genomics.

As is logical in one of Europe's leading agricultural and fishing regions, all three Galician universities also devote considerable attention to research into food technology, farm production, the sustainable management of marine resources, and aquaculture. In particular, together with centers belonging to the Spanish Higher Council for Scientific Research (CSIC; www.csic.es) and the Spanish Institute of Oceanography (www.ieo.es), they constitute a powerful marine research network that places Galicia at the forefront in this area.

More generally, Galicia has sought to maximize the social and economic value of its natural heritage, and its efforts in this respect include extensive research in environmental sciences, a vital strategic area in which particularly significant work is being done in the design of water treatment plants, the sustainable management of resources, alternative energy sources, and other areas of the fields of environmental engineering and bioprocess development.

In the dynamic field of information technologies and communications (ITC), the areas of competence of the three universities complement each other, and jointly cover software, hardware and telecommunications issues. In A Coruña, the recently inaugurated Software Technologies Research Center brings together private enterprise and research groups belonging to the University's Computer Science Faculty. This latter maintains an impressive capacity to generate technology and business initiatives, and its 2,300-odd students have few worries about their insertion in the labor market.

The software development vocation of A Coruña is complemented by the University of Vigo's competence in the areas of telecommunications and electronics, and by Santiago's expertise in hardware engineering. This wide range of advanced know-how

Galician universities are a splendid choice for scientists looking to develop their careers at the highest level, as is testified to by their annual output of more than 400 PhDs.

gives Galicia a sharp competitive edge in the ICT industry, especially in relation to the audiovisual sector, which is strongly represented here. And if A Coruña has its Software Technologies Research Center, since December 2007 Vigo has the Gradiant Center (acronym of Galician Research and Development Center in Advanced Telecommunications; www.gradiant.org). This entity draws on multinational ICT corporations and other enterprises, ICT researchers from the three Galician universities, and the main communications operators in the region, and has put Galicia on a par with Catalonia as regards innovation and R&D in fields such as digital communications and the development of networks and applications.

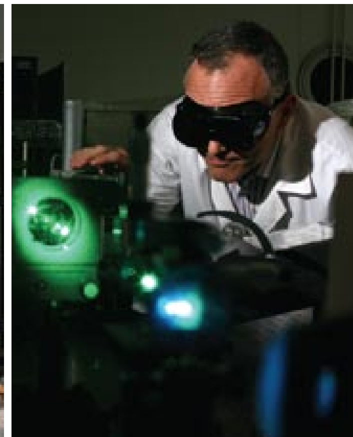
In addition to the centers mentioned above, the commitment of the Galician universities to the application of their know-how by local private enterprise has led to the creation and growth of science parks and industry-oriented technology centers serving sectors such as ceramics, construction and civil engineering, shipping, plastics, the auto and energy industries, and milk and meat production. In these institutions, private companies have access to university technological services that assist them in keeping abreast of technological innovation and provide them with researchers and technologists who have been trained in the latest production processes.

Finally, the importance afforded to the practical application and exploitation of scientific and technological expertise has not prevented the establishment of equally active centers in which basic research is pursued in such fields as biological chemistry, molecular medicine, marine science, environmental management, animal experimentation, and life sciences and technologies. Designed to perform and achieve at the highest level in accordance with international standards, these institutions are entrusted with the task of creating and developing the research fields of the future.

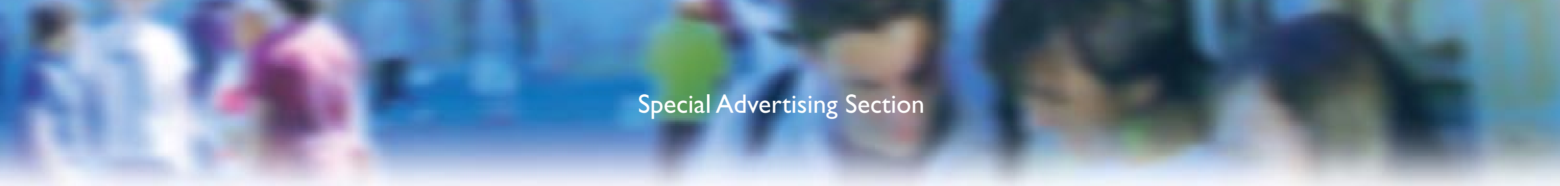
Arts and Social Sciences

While its cultural roots go back to prehistoric times, Galicia is today a modern European welfare society characterized by the impartiality and universality of its educational, social, health and cultural services. As is logical in this context, education and research in the social sciences, law, the arts and fine arts feature large in Galician universities. Their high standards in areas such as cultural heritage management, literature and history contribute both to the maintenance of Galicia's peculiar personality and to the development of a dynamic cultural and tourist industry that attends to visitors attracted partly by the rich historic, artistic and architectural heritage of cities such as Santiago de Compostela and Lugo (both of them UNESCO World Heritage sites), and partly by a natural heritage that includes areas designated as UNESCO biosphere reserves and other internationally recognized nature reserves. Similarly, their sound tradition and imaginative initiatives in law, economics and education interpret and contribute to social and economic change, and to the development and growth of a demanding society that is proud of possessing its own identity and culture within Europe, yet open to the entire world.

Historically, Galicia's rich culture developed around its language, Galician, a Romance language with the same origins as Portuguese. Today, Galician cohabits harmoniously with Castilian Spanish, creating a social environment that both favors multilingualism and encourages the study of linguistic phenomena.





The Universities of Galicia, which are integrated in the European Space for Higher Education, offer 177 official first degree programs characterized by their academic quality.

SUG
Sistema Universitario de Galicia

University Support for Entrepreneurship

In Spain, the SUG has been a pioneer in the field of university support of young entrepreneurs, having taken the lead in promoting the creation of companies that exploit the knowledge and know-how of its universities' researchers. Its Uniemprende program (www.uniemprende.com), which provides technical and financial support for the development of promising science- or technology-based ideas into viable businesses, has set over a hundred budding enterprises on the road to success. Involving not only the three universities but also major finance houses and Galician industrial corporations, it was the foundation stone of an enterprise support system that now includes the business incubator Uninova (www.uninova.org), the venture capital company Unirisco (www.unirisco.org), and the business angel network Uniban (www.uniban.org), the first such network to have been promoted by a public Spanish university.

Galician Universities and the World

With the international relevance of its capabilities and goals in research and higher education, Galicia offers the vigor and academic excellence of its universities to the rest of Europe and the world. Its scientific activities now enjoy the patronage of such respected bodies as the Bill and Melinda Gates Foundation, the European Space Agency, the World Health Organization (WHO), and the United Nations Educational, Scientific and Cultural Organization (UNESCO), which currently fund projects with economic and social impact that are being pursued by international scientific consortia led by Galician researchers.

In keeping with this international vocation is another of the Galician universities' strengths: support of the international mobility of their students and researchers. The SUG universities are active members of a number of international research networks and of inter-university consortia such as the Compostela Group of European universities (www.grupocompostela.org), and have bilateral cooperation agreements with more than 300 universities around the world. They also promote their students' mobility through their participation in the European Union's Erasmus and Erasmus Mundus programs. In the other direction, together they would rank among the top 25 European universities as regards the number of students hosted under Erasmus.

Galicia: Living History

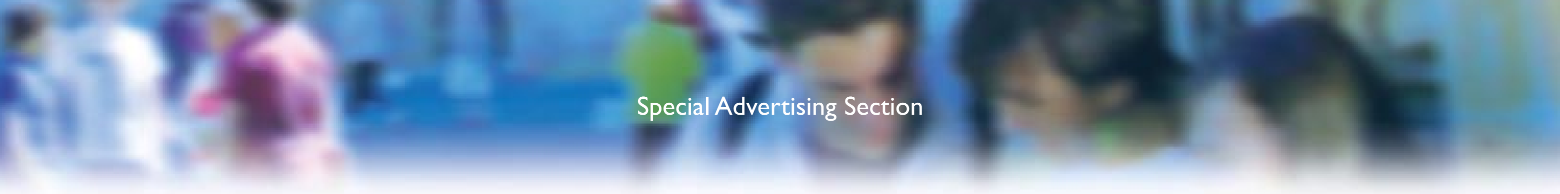
Some 2,000 years ago the Romans situated Finis Terrae, the terminal point of the world as they knew it, in Galicia. Since then, this region of Europe has become an historical and cultural landmark that, far from being the end of the world, welcomes guests from far beyond to the Old Continent with its own peculiar traditions and personality.

Cultural events and historic architecture are particularly abundant in the university cities. These are all connected with each other and with the picturesque towns of the surrounding countryside by a modern communications network; while Galicia's three airports, located on the outskirts of the cities that harbor the main campuses of the Universities of Santiago de Compostela, Vigo, and A Coruña, connect the region with the rest of Europe and the world.

In Galicia, mountain mingles with sea in a land bathed in green, in which its trees and waters are the basis of its immense natural heritage. Approximately 70% of its total surface area is afforested, and its landscape is traversed by more than a thousand rivers that merge to meet the sea on a coastline characterized by its rías, great tidal estuaries bestrewn with beautiful beaches and islands.

Galicia's mild, humid Atlantic climate, with its pleasant temperatures, provides the perfect conditions for its exceptional farming industry, which cohabits in harmony with an industrialized urban society. Quality of life is a priority in a community with universal access to free public education and health services, and where the university system, too, is public and is firmly implanted in social and economic structures.

Abounding in natural and cultural riches, and with a capital, Santiago de Compostela, that is a focus of pilgrimage and a symbol of European integration, Galicia constitutes a fascinating environment in which to enjoy a fruitful academic experience that can easily be continued in other parts of Europe thanks to the close academic links among the universities of all European nations.



University of Santiago:
www.usc.es
Tradition and Pioneer Spirit

With more than 500 years of history behind it, the University of Santiago de Compostela (USC) is an academic leader in higher education, research, and the promotion of enterprise.

- Founded in 1495, it is situated in a privileged urban setting declared a UNESCO World Heritage Site.
- It has three campuses: two in Santiago de Compostela and another in Lugo, 62 miles away.
- It comprises 32 Faculties and Schools of Higher Education that offer 70 first degree courses, 19 master's degree courses, and 69 doctorate programs.
- It has 23 specialized research centers, making it one of Spain's leading universities in scientific research and the training of researchers.
- Among other disciplines included within its broad scope, its research activity stands out in the fields of Biotechnology, Biomedicine, Pharmaceutical Chemistry, Physics, Chemistry, ICT Hardware, Environmental Science, Aquaculture, Philology, and History.
- USC was the original promoter of the Compostela Group of European universities, which with the Way of St. James and European culture as its symbolic and spiritual axes comprises 80 universities in 25 countries.

UNIVERSIDADE DA CORUÑA

University of A Coruña:
www.udc.es
Connecting with Society

In keeping with its surroundings, the University of A Coruña offers modernity, drive, innovation, and openness to the world in an institutional environment with the placement of its graduates as its primary goal.

- In addition to the main campuses in A Coruña, it has another two in Ferrol, 32 miles to the northeast.
- It comprises 25 Faculties and University Schools that offer 25 first degree courses, 27 master's degree courses, and 43 doctorate programs.
- Its teaching and research activity is strategically concentrated in the areas of ICT Software, Architecture and Civil Engineering, Industrial Production (specializing in the shipping industry), Environmental Science, and Health Sciences.
- Much of its research is carried out in technology centers that are jointly funded by the public and private sectors, thus integrating academia with industry through a highly flexible management strategy based on corporate entities run in accordance with business criteria.

UNIVERSIDADE DE VIGO

University of Vigo:
www.uvigo.es
Technology as a Guiding Light

Quality, innovation, and its position as a technological front-runner characterize the youngest of Galicia's universities, which is committed to the forging of direct links between higher education and industry in the most dynamic economic and urban environment in Galicia.

- The University has three campuses, located in the cities of Vigo, Pontevedra, and Ourense.
- It comprises 27 Faculties and University Schools that offer 57 first degree courses, 30 master's degree courses, and 48 doctorate programs.
- Its teaching and research activity is strategically concentrated in the areas of Chemistry, Ecology and Animal Biology, Food Safety and Quality, Marine Sciences, Economics, Renewable Energies, and ICT.
- Its Technology City project agglutinates the efforts of academia and those of commercial, industrial and financial interests in creating an ideal environment for researchers and students to pursue their activities in a competitive professional setting.
- A pioneer in the field of distance learning, it has a modern e-learning platform that complements classroom and laboratory teaching.

SciAm Perspectives

Questions for Would-be Presidents

For the science-policy positions of McCain and Obama to be meaningful, they need to be more detailed

BY THE EDITORS

MATT COLLINS

No one has ever complained that U.S. presidential candidates talk too much about science, and this year has been no exception. Nevertheless, science-related issues such as energy and health care, once viewed as sideshows, have taken center stage in this election. The candidates' positions are often vague, but they are an improvement on past campaigns. Here are some follow-up questions that they invite.

Energy. Both John McCain and Barack Obama have called for a cap-and-trade system to cut carbon emissions, although Obama's proposed reduction (80 percent from 1990 levels by 2050) is larger than McCain's (65 percent). Both candidates, however, need to answer a crucial question: Why cap-and-trade when so many policy experts, seeing the troubles with carbon trading in Europe, now recommend a simpler carbon tax?

Both candidates oppose Yucca Mountain, the controversial proposed nuclear waste dump. McCain has advocated an "international repository" instead. What is the difference? Where does Obama propose to put the waste? The U.S. has spent 30 years studying Yucca; switching sites will restart the clock. What will nuclear plants do with all their spent fuel in the meantime?

Beyond these generalities, the candidates diverge. McCain would subsidize the construction of 45 new nuclear reactors, costing upward of $270 billion and taking 20 years to complete. Why invest that much public money in nuclear rather than solar or wind power, which could start pumping out watts much sooner? How would offshore oil drilling, which McCain has urged, help wean the nation off fossil fuels?

Obama has spelled out intermediate milestones for emissions reductions and specific targets for biofuels and other renewables. How would these goals be enforced? He has promised $150 billion over 10 years for energy research and development as well as a $10-billion-a-year venture capital fund. What would stop that money, as in so many past efforts, from being allocated by lobbyists rather than engineers? Does the energy industry really need more venture capital? Oddly, he has promised to "fight the efforts of big oil and big agribusiness to undermine" corn-based ethanol. How has agribusiness sought to undermine corn ethanol? If anything, it seems rather the opposite. And why sustain support for corn ethanol when it is the most ungreen of all biofuels?

Embryonic stem cells. Both McCain and Obama support harvesting stem cells from embryos left over from in vitro fertilization. McCain would ban scientists from using donor eggs to create disease-specific stem cell lines or chimeric animals to see how human stem cells behave during development. How, then, would his policy be substantially different from the current highly restrictive one, and how would it encourage the discovery of lifesaving treatments? As for Obama, what alternative sources of embryonic cells would he permit? What federal oversight should embryonic stem cell research have that other forms of biomedical research, including those involving human subjects, do not already have?

Space. Both candidates support President George W. Bush's plan to send astronauts to the moon and then to Mars. Are McCain and Obama willing to increase NASA's budget commensurately, or would they beggar the space science programs?

Other topics. Obama, more than McCain, has taken positions on many other science issues. He has promised to double federal funding for basic research. Over what period? And does that figure include his promised energy investment? He has said he would appoint a chief technology officer to protect citizens' electronic privacy, but could that person really overrule federal agencies with their own prerogatives? How precisely would Obama make good on his vow to reform the troubled copyright and patent system? Both candidates clearly need to flesh out their ideas if those ideas are to rise above throwaway campaign pledges and become real policy. ■

SCI AM
For further coverage of science and the election, including links to statements by third-party candidates, see **www.SciAm.com/election2008**

Sustainable Developments

Coping with a Persistent Oil Crisis

With global demand for cars accelerating, the best approach is to redesign cars and transport systems

BY JEFFREY D. SACHS

According to recent statistics, U.S. motorists have responded to record-high prices at the pump by driving less. Any hope that this cutback will significantly restrain global oil prices is misplaced, however: fundamental factors of supply and demand will keep oil costly for years to come. Although U.S. drivers account for around 13 million barrels a day (mbd) out of 85 mbd of worldwide demand, the growth in driving in China, India and other developing countries will easily outstrip any cutback in U.S. demand.

Crude oil production in the Persian Gulf has been nearly flat at just over 20 mbd since the early 1970s. The growth in world supply since that time has come from oil fields outside the Middle East, but many of them have reached their production limits and important ones are in decline. There are few prospects for megadiscoveries that could keep up with fast-growing world demand.

The 18 billion barrels or so that is supposedly economically accessible in protected U.S. offshore sites would slake around seven months of global demand in 2008 and a much smaller share by the time they reached the market in 10 to 15 years. And these small gains would come at enormous environmental risks.

Today China has around 50 million cars, trucks and buses (roughly 40 per 1,000 people), compared with around 250 million in the U.S. (roughly 800 per 1,000 people). If China attains just half of the U.S. per capita ownership of passenger vehicles, it would have some 500 million of them, roughly twice as many as the U.S. Engineering advances in automobile production will dramatically accelerate the trend. Low-cost cars such as the Tata Nano, India's newly unveiled $2,500 compact sedan, will bring auto ownership within reach of hundreds of millions of newly middle-class households in the coming decades. Currently around 900 million cars, trucks and buses are on the road worldwide. China and India alone could add another 25 million to 30 million vehicles per year in a decade; they could plausibly add another 600 million within 30 years. Conventional oil has little prospect of keeping up with this soaring demand.

Of course, a grave economic crisis—war, global depression, collapse of one or more major economies—would cut oil demand the hard way. There are two much better alternatives.

The first is a redesigned, far more energy-efficient vehicle that uses low-carbon-emitting energy carriers such as electricity or hydrogen. Variants of plug-in hybrids and all-battery cars have been promised by major auto producers as early as 2010, and demonstration hydrogen fuel-cell cars are also expected around then.

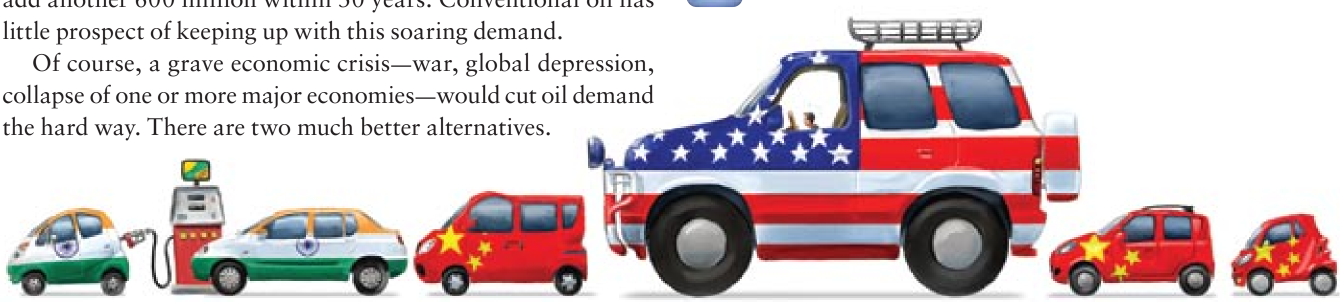
Unresolved problems of cost, performance and infrastructure face these technologies. Public funding for technological research, development and demonstration and for supporting infrastructure should be deployed to ensure a timely changeover to new energy-efficient (and low carbon dioxide–emitting) vehicles. Any electric or hydrogen option will require large-scale deployment of new low-emissions electricity generation, such as solar, wind, nuclear and coal plants that capture and sequester carbon dioxide.

The second alternative is a gradual reconfiguration of city life to reduce our dependence on driving and raise our reliance on walking, cycling and taking public transport. Despite free-market ideological presumptions, urban sprawl is at least as much a function of zoning and the provision of public infrastructure (for example, roads versus light rail) as it is of individual choices.

The current energy crisis will most likely worsen before it gets better. It threatens to create a prolonged period of stagflation, increased oil skirmishes and even oil wars, and further marginalization of the poor, who will find themselves priced out of transport and perhaps even out of food if the U.S. keeps up its dangerous policy of converting corn to ethanol fuel. Yet it could also be the critical spur to action, prompting vital changes in technologies and lifestyles. It's not too late to take the more productive path, but time is running out. ■

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

SCI AM An extended version of this essay is available at **www.SciAm.com/oct2008**



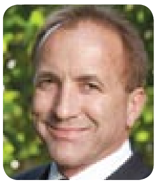
PHOTOGRAPH BY BRUCE GILBERT/EARTH INSTITUTE; ILLUSTRATION BY MATT COLLINS

Skeptic

A Random Walk through Middle Land

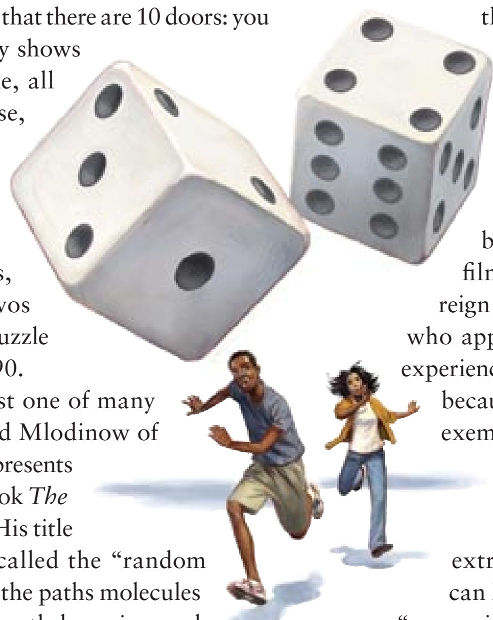
How randomness rules our world and why we cannot see it, Part 2

BY MICHAEL SHERMER



Imagine that you are a contestant on the classic television game show *Let's Make a Deal*. Behind one of three doors is a brand-new automobile. Behind the other two are goats. You choose door number one. Host Monty Hall, who knows what is behind all three doors, shows you that a goat is behind number two, then inquires: Would you like to keep the door you chose or switch? Our folk numeracy—our natural tendency to think anecdotally and to focus on small-number runs—tells us that it is 50–50, so it doesn't matter, right?

Wrong. You had a one in three chance to start, but now that Monty has shown you one of the losing doors, you have a two-thirds chance of winning by switching. Here is why. There are three possible three-doors configurations: (1) good, bad, bad; (2) bad, good, bad; (3) bad, bad, good. In (1) you lose by switching, but in (2) and (3) you can win by switching. If your folk numeracy is still overriding your rational brain, let's say that there are 10 doors: you choose door number one, and Monty shows you door numbers two through nine, all goats. Now do you switch? Of course, because your chances of winning increase from one in 10 to nine in 10. This type of counterintuitive problem drives people to innumeracy, including mathematicians and statisticians, who famously upbraided Marilyn vos Savant when she first presented this puzzle in her *Parade* magazine column in 1990.



The "Monty Hall Problem" is just one of many probability puzzles physicist Leonard Mlodinow of the California Institute of Technology presents in his delightfully entertaining new book *The Drunkard's Walk* (Pantheon, 2008). His title employs the metaphor (sometimes called the "random walk") to draw an analogy between "the paths molecules follow as they fly through space, incessantly bumping, and being bumped by, their sister molecules," and "our lives, our paths from college to career, from single life to family life, from first hole of golf to eighteenth." Although countless random collisions tend to cancel one another out because of the law of large numbers—where improbable events will probably happen given enough time and opportunity—every once in a great while, "when pure luck occasionally leads to a lopsided preponderance of hits from some particular direction … a noticeable jiggle occurs." We notice the improbable directional jiggle but ignore the zillions of meaningless and counteracting collisions.

In the Middle Land of our ancient evolutionary environment, which I introduced in Part 1 of this column last month, our brains never evolved a probability network, and thus our folk intuitions are ill equipped to deal with many aspects of the modern world. Although our intuitions can be useful in dealing with other people and social relationships (which evolved as common and important for a social primate species such as ours when we were struggling to survive in the harsh environs of the Paleolithic), they are misleading when it comes to such probabilistic problems as gambling. Let's say you are playing the roulette wheel and you hit five reds in a row. Should you stay with red because you are on a "hot streak," or should you switch because black is "due"? It doesn't matter, because the roulette wheel has no memory, yet gamblers notoriously employ both the "hot streak fallacy" and the "dueness fallacy," much to the delight of casino owners.

Additional random processes and our folk numeracy about them abound. The "law of small numbers," for example, causes Hollywood studio executives to fire successful producers after a short run of box-office bombs, only to discover that the subsequent films under production during the producer's reign became blockbusters after the firing. Athletes who appear on *Sports Illustrated*'s cover typically experience career downturns, not because of a jinx but because of the "regression to the mean," where the exemplary performance that landed them on the cover is itself a low-probability event that is difficult to repeat.

Extraordinary events do not always require extraordinary causes. Given enough time, they can happen by chance. Knowing this, Mlodinow says, "we can improve our skill at decision making and tame some of the biases that lead us to make poor judgments and poor choices … and we can learn to judge decisions by the spectrum of potential outcomes they might have produced rather than by the particular result that actually occurred." Embrace the random. Find the pattern. Know the difference. ■

Michael Shermer is publisher of Skeptic *(www.skeptic.com). His latest book is* The Mind of the Market.

PHOTOGRAPH BY BRAD SWONETZ; ILLUSTRATION BY MATT COLLINS

Anti Gravity

Fuel's Errand

What each state can bring to the hunt for oil alternatives

BY STEVE MIRSKY

***New York Times* columnist** Thomas L. Friedman has a new book out called *Hot, Flat, and Crowded: Why We Need a Green Revolution—and How It Can Renew America.* He makes the case that going green isn't bad for the economy—in fact, it's the only way for America to remain an economic leader. I interviewed Friedman for the weekly *Scientific American* podcast (available at www.SciAm.com/podcast). And an abridged Q&A version of that interview can be found on page 14.

But something came up during our conversation worth closer consideration during the homestretch of this protracted presidential campaign.

I'd long suspected that the enthusiasm for ethanol was really an enthusiasm of politicians for pandering to Iowa's corn constituents. Because ethanol from corn has many downsides—higher food prices, more water for irrigation, possible losses in nutritional value of the soil, potentially higher levels of ozone output from car exhaust, and more. So I asked Friedman, "Would corn ethanol even be on the table if Iowa didn't have the first caucus?" Friedman replied, "There is no question; it would not be on the table. This is another form of agricultural welfare in my view."

So I got to wondering, what fuels in abundant supply could the other 49 states offer as alternatives if they led off the presidential sweepstakes?

Alabama: Confederate flags; Confederate flag blankets; Confederate flag posters; Confederate flag car window decals.

Alaska: Electrons flowing through Ted Stevens's series of tubes.

Arizona: Solar, along with "My Grandson Is an Honor Student" bumper stickers. Plus, see Florida.

Arkansas: Hope. And the oil coating its feathers.

California: Any remaining marijuana not being used medicinally.

Colorado: Coors beer. (The pressurized carbonation, not the trace amounts of ethanol.)

Connecticut: Potential energy stored as extreme jaw tension.

Delaware: Virtually endless supply of credit-card junk-mail applications.

Florida: Medicare forms; Bengay tubes. Plus, see Arizona and Alabama.

Georgia: Peaches; whatever is actually in Caffeine-Free Diet Coke; Jimmy Carter poetry.

Hawaii: Thermal from Kilauea; petroleum-based long-chain polymer leis.

Idaho: Recovered french fry oil; Larry Craig's toe-tapping nervous energy.

Illinois: Land of Lincoln logs.

Indiana: Hoosier Hysteria; Indy 500 fuel spills.

Kansas: Elmira Gulch bicycle power.

Kentucky: Bourbon; cellulosic ethanol processed by thoroughbred horses.

Louisiana: Hydroelectric at the 17th Street Canal.

Maine: Pages emerging from Stephen King's printer.

Maryland: References to Johns Hopkins as John Hopkins, Johns Hopkin or John Hopkin.

Massachusetts: Wind power of Red Sox fans doing anti-Yankees chants at all home games, including those the Yankees aren't in.

Michigan: Unsold SUVs.

Minnesota: Lake power (needs a lot more work); mosquito wing movements.

Mississippi: Double letters; see Alabama.

Missouri: Snide remarks about Kansas.

Montana: Joe; Hannah.

Nebraska: Angst produced by driving the entire 455 miles across I-80 without even making a stop at Cabela's.

Nevada: What gets drilled here stays here.

New Hampshire: "I Climbed Mt. Washington" bumper stickers.

New Jersey: Offal from Satriale's Pork Store; hair gel.

New Mexico: Turquoise jewelry.

New York: Subterranean ticker tape deposits; broke brokers.

North Carolina: Unfinished furniture; offal from all the pig farms stocking Satriale's.

North Dakota: Vacuum energy.

Ohio: I-dotting energy of the Ohio State sousaphone player.

Oklahoma: Panhandlers.

Oregon: Ways to say Oregon.

Pennsylvania: Lancaster County's unused electricity; apple butter.

Rhode Island: Quahog's emetic chowdah!

South Carolina: Miss Teen South Carolina's responses to pageant questions.

South Dakota: Giant sculptures; pronghorn pronks.

Tennessee: Al Gore's awards.

Texas: Big, bright night star photons; wide, high prairie sky wind.

Utah: Osmonds.

Vermont: Maple syrup supercharged with dairy cow methane.

Virginia: William and Mary; Joey and Mary; Frankie and Mary …

Washington: Tourists looking for the Lincoln Memorial.

West Virginia: Discarded mine safety regulations.

Wisconsin: Brett Favre retirement speeches; cheese curds.

Wyoming: Unused half of Dick Cheney's smile. ■

PHOTOGRAPH BY FLYNN LARSEN; ILLUSTRATION BY MATT COLLINS

METEOROLOGY

What We've Learned From Storm Chasing
Speaker: **Howard B. Bluestein, Ph.D.**

Dr. Howard Bluestein has been chasing severe thunderstorms and tornadoes in the Southern Plains of the U. S. for the past three decades. What WAS he thinking? Join Dr. Bluestein and he'll lay out his primary objectives: trying to understand what causes storms and how the wind field varies within them, with the ultimate goal of saving lives.

Glimpse the big picture of the excitement of the chase and the unique beauty of tornadoes when passing over the open countryside destroying nothing but grass and dirt. Get the details on what Dr. Bluestein and colleagues have learned from their field work and what it is really like to be a storm chaser while trying to collect data and remain safe.

Tornadoes and Severe Thunderstorms: What We've Learned From Numerical Simulations

While atmospheric scientists gather real-world data and thrills from chasing tornadoes and severe thunderstorms, they can't perform controlled experiments on storms in the real world.

In order to understand what causes some thunderstorms to produce severe weather and others to not, meteorologists conduct carefully controlled experimental simulations. Dr. Howard Bluestein will orient you to the practice of simulating, fairly realistically, severe thunderstorms and to a more limited extent, tornadoes

If you'd like to know how scientists depict Mother Nature in the computer lab, what Dr. Bluestein and colleagues have learned from numerical simulations of severe weather and how it relates to observational field programs, this is the session for you.

Forecasting Severe Weather

Unbelievable to us today, the issuance of severe thunderstorm and tornado warnings was once banned because it was feared that the populace would panic. Throwing caution to the wind, U.S. meteorologists in the late 1940s made the first attempts to forecast severe weather based on pattern recognition, and amazingly it worked!

Dr. Bluestein will update you on the state of the forecaster's art and science. Equipped with an increased understanding of why storms form, a much better national observing network, Doppler radars, satellites, and computer models, meteorologists can forecast severe weather better than ever. . . but are still not able to predict which thunderstorms will produce tornadoes and which will not.

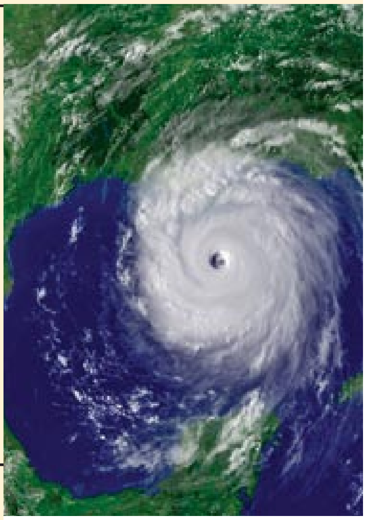
Visit the frontier of forecasting with Dr. "Cb" and pick up the advances in using cloud models and Doppler radar data as input to make forecasts of individual thunderstorms, and in "ensemble" forecasting which averages many forecasts having slightly different initial conditions and/or model physics.

Radars as Tools of Choice: Better Living Through Radiation

Radar is the tool of choice to monitor and observe severe weather systems because it probes dangerous storms remotely with amazing detail.

Take a look with Dr. Bluestein at how the radar signal is related to precipitation intensity, how wind information is gathered by Doppler radar, and how polarimetric radars provide useful information that allows us to distinguish rain from hail from snow from airborne cows.

Learn the latest about new phased-array radar systems that can electronically scan an entire storm in less than 10 seconds, and gain insights on future directions for radar in meteorology.



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ASTROPHYSICS & COSMOLOGY

A Brief History of Our Universe
Speaker: **Max Tegmark, Ph.D.**

With a cosmic flight simulator, we'll take a scenic journey through space and time. After exploring our local Galactic neighborhood, we'll travel back 13.7 billion years to explore the Big Bang itself and how state-of-the-art measurements are transforming our understanding of our cosmic origin and ultimate fate.

The Mysterious Dark Side of Cosmology: Dark Matter And Dark Energy

A recent avalanche of accurate measurements has revolutionized our understanding of cosmology, but also stumped us with new puzzles. What are the dark matter and dark energy that together make up 96% of the stuff in our universe? Learn about some of the most promising dark matter and dark energy candidates, and some of the experiments that may solve these mysteries in the next few years.

How Did It All Begin — Or Did It? How Will It All End?

Although we humans have undoubtedly asked these questions for as long as we've walked the Earth, we've made spectacular progress on them in recent years, forcing us to discard much of what cosmology textbooks told us up until quite recently. Get the latest on competing ideas, their implications and how they can be experimentally tested.

Questions, I've Got Questions: Black Holes Edition

Take a look at some of the most spectacular recent evidence that black holes really exist. Dr. Tegmark will cover what we know about them and what remains mysterious. Are black holes in fact crucial to enable galaxies to form? Can black holes form new universes in their interiors? Plus, using a fully general-relativistic flight simulator, you'll take a scenic orbit of the monster black hole at the center of our Galaxy and discuss how one could actually make this dizzying journey with only modest energy expenditure.

Parallel Universes

Is physical reality larger than the part that we can observe? Dr. Tegmark argues that not only are parallel universes likely to exist, but that there may be as many as four different levels of them, related to infinite space, cosmological inflation, quantum mechanics and mathematical structures.

Cosmology And the Meaning of Life

When gazing up on a clear night, it's easy to feel small and insignificant. Join Dr. Tegmark for a status report on the search for extrasolar planets and extraterrestrial life. Might cosmic life be much rarer than one might guess, making our planet the most significant place in our entire observable universe? We'll discuss and speculate about possible long-term futures for life on earth and in the cosmos.

BASEBALL: IT'S NOT NUCLEAR PHYSICS. OR IS IT?

When Ash Meets Cowhide: The Physics of Hitting A Home Run
Speaker: **Alan M. Nathan, Ph.D.**

For a baseball fan, there are few things more satisfying than hearing that sharp distinctive crack of the bat announcing that the ball is on its way to the centerfield seats. For a physicist, there are few things more satisfying than figuring out how something works. And for a physicist who is also a baseball fan, it is pure ecstasy to have figured out much of what is going on during that very brief instant of time when ash meets cowhide. Dr. Nathan will try to convey a bit of that excitement as he steps you through the physics of hitting a home run.

The Controversy Over Aluminum Bats

Get a grip on the core issues in play in the aluminum vs. wooden bat dialogue. Hollow metal bats are superior to wood bats as hitting instruments. Because of aluminum bats' effect on hits, they also raise safety questions. Both these issues have lead some organizations to actually ban the use of aluminum bats in officially sanctioned games.

In this session, you'll examine the performance differences between wood and non-wood bats from a physics perspective. Dr. Nathan will lay out the underlying physics behind the techniques currently used by governing bodies such as the NCAA to regulate the performance of nonwood bats. Learn how well those techniques work in limiting the performance gap between wood and aluminum. Get the facts and prevailing opinions across the spectrum of baseball.

The Aerodynamics of Excitement: Curveballs, Gyroballs, Towering Popups, and Tape Measure Home Runs

Where would the game of baseball be without aerodynamics? Played in a vacuum, the curve ball wouldn't curve and home runs would travel over 700 ft. The trajectory of a baseball in flight, whether it is a pitched or batted ball, is very different from the one we teach in introductory physics courses, where the effects of the interaction of the ball with the air are neglected. In this talk with Dr. Nathan, you'll learn what we know about the aerodynamics of a baseball and how we know it (but not when we knew it). Get the inside scoop on the high-tech tools now being used to study the trajectories of baseballs.

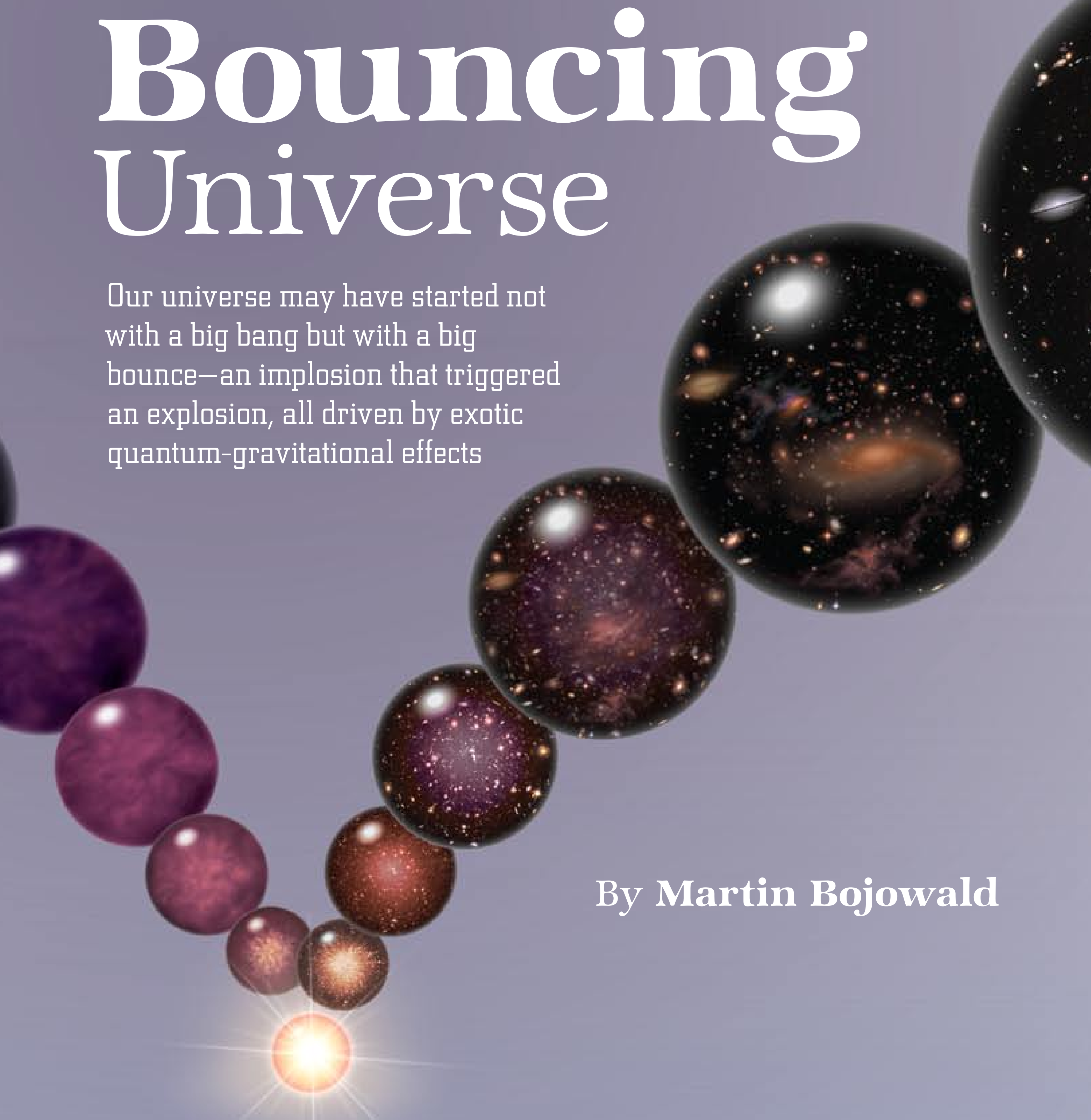
Are Barry Bonds' Home Run Records Tainted?

In 2001, Barry Bonds hit 73 home runs, three more than the previous single-season home run record. In 2007, he hit his 756th career home run, passing Hank Aaron's golden career record.

Bonds is alleged to have used performance-enhancing drugs. If indeed someone were to use such drugs, how might that have affected home run production? At the risk of dampening enthusiastic Bonds-related debates everywhere, Dr. Nathan will go into a scientific framework for answering this question. You'll come away equipped with knowledge of the factors and influences bearing on a slugger's performance that we can quantify with confidence, those about which we can offer an educated guess, and those that are poorly understood.

Follow the **Bouncing** Universe

Our universe may have started not with a big bang but with a big bounce—an implosion that triggered an explosion, all driven by exotic quantum-gravitational effects



By **Martin Bojowald**

PAT RAWLINGS *SAIC*

Atoms are now such a commonplace idea that it is hard to remember how radical they used to seem. When scientists first hypothesized atoms centuries ago, they despaired of ever observing anything so small, and many questioned whether the concept of atoms could even be called scientific. Gradually, however, evidence for atoms accumulated and reached a tipping point with Albert Einstein's 1905 analysis of Brownian motion, the random jittering of dust grains in a fluid. Even then, it took another 20 years for physicists to develop a theory explaining atoms—namely, quantum mechanics—and another 30 for physicist Erwin Müller to make the first microscope images of them. Today entire industries are based on the characteristic properties of atomic matter.

Physicists' understanding of the composition of space and time is following a similar path, but several steps behind. Just as the behavior of materials indicates that they consist of atoms, the behavior of space and time suggests that they, too, have some fine-scale structure—either a mosaic of spacetime "atoms" or some other filigree work. Material atoms are the smallest indivisible units of chemical compounds; similarly, the putative space atoms are the smallest indivisible units of distance. They are generally thought to be about 10^{-35} meter in size, far too tiny to be seen by today's most powerful instruments, which probe distances as short as 10^{-18} meter. Consequently, many scientists question whether the concept of atomic spacetime can even be called scientific. Undeterred, other researchers are coming up with possible ways to detect such atoms indirectly.

The most promising involve observations of the cosmos. If we imagine rewinding the expansion of the universe back in time, the galaxies we see all seem to converge on a single infinitesimal point: the big bang singularity. At this point, our current theory of gravity—Einstein's general theory of relativity—predicts that the universe had an infinite density and temperature. This moment is sometimes sold as the beginning of the universe, the birth of matter, space and time. Such an interpretation, however, goes too far, because the infinite values indicate that general relativity itself breaks down. To explain what really happened at the big bang, physicists must transcend relativity. We must develop a theory of quantum gravity, which would capture the fine structure of spacetime to which relativity is blind.

The details of that structure came into play under the dense conditions of the primordial universe, and traces of it may survive in the present-day arrangement of matter and radiation. In short, if spacetime atoms exist, it will not take centuries to find the evidence, as it did for material atoms. With some luck, we may know within the coming decade.

Pieces of Space

Physicists have devised several candidate theories of quantum gravity, each applying quantum principles to general relativity in a distinct way. My work focuses on the theory of loop quantum gravity ("loop gravity," for short), which was developed in the 1990s using a two-step procedure. First, theorists mathematically reformulated general relativity to resemble the classical theory of electromagnetism; the eponymous "loops" of the theory are analogues of electric and magnetic field lines. Second, following innovative procedures, some that are akin to the mathematics of knots, they applied quantum principles to the loops. The resulting quantum gravity theory predicts the existence of spacetime atoms [see "Atoms of Space and Time," by Lee

KEY CONCEPTS

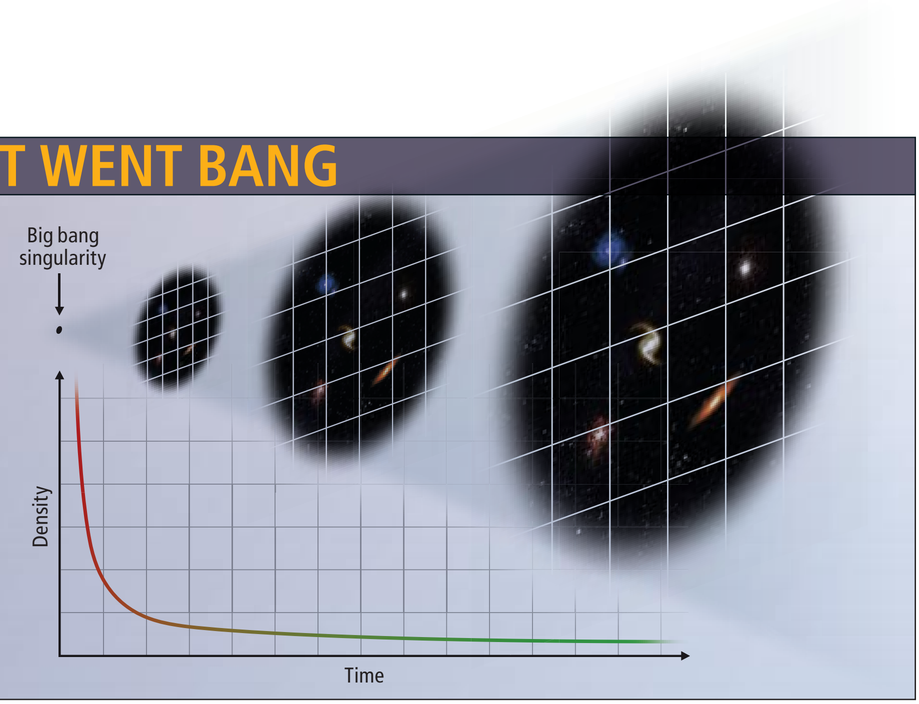
- Einstein's general theory of relativity says that the universe began with the big bang singularity, a moment when all the matter we see was concentrated at a single point of infinite density. But the theory does not capture the fine, quantum structure of spacetime, which limits how tightly matter can be concentrated and how strong gravity can become. To figure out what really happened, physicists need a quantum theory of gravity.
- According to one candidate for such a theory, loop quantum gravity, space is subdivided into "atoms" of volume and has a finite capacity to store matter and energy, thereby preventing true singularities from existing.
- If so, time may have extended before the bang. The pre-bang universe may have undergone a catastrophic implosion that reached a point of maximum density and then reversed. In short, a big crunch may have led to a big bounce and then to the big bang.

—The Editors

[THE PROBLEM]

THE THEORY JUST WENT BANG

The idea of the big bang comes from a simple observed fact: galaxies in the universe are moving apart. If you play this trend back in time, galaxies (or their precursors) must have been all scrunched up 13.7 billion years ago. In fact, according to Einstein's general theory of relativity, they were scrunched into a single point of infinite density—the big bang singularity. But an infinite density is unrealistic: that relativity theory predicts it is a sign that the theory is incomplete.



Smolin; Scientific American, January 2004].

Other approaches, such as string theory and so-called causal dynamical triangulations, do not predict spacetime atoms per se but suggest other ways that sufficiently short distances might be indivisible [see "The Great Cosmic Roller-Coaster Ride," by Cliff Burgess and Fernando Quevedo; Scientific American, November 2007, and "The Self-Organizing Quantum Universe," by Jan Ambjørn, Jerzy Jurkiewicz and Renate Loll; Scientific American, July]. The differences among these theories have given rise to controversy, but to my mind the theories are not contradictory so much as complementary. String theory, for example, is very useful for a unified view of particle interactions, including gravity when it is weak. For the purpose of disentangling what happens at the singularity, where gravity is strong, the atomic constructions of loop gravity are more useful.

The theory's power is its ability to capture the fluidity of spacetime. Einstein's great insight was that spacetime is no mere stage on which the drama of the universe unfolds. It is an actor in its own right. It not only determines the motion of bodies within the universe, but it evolves. A complicated interplay between matter and spacetime ensues. Space can grow and shrink.

Loop gravity extends this insight into the quantum realm. It takes our familiar understanding of particles of matter and applies it to the atoms of space and time, providing a unified view of our most basic concepts. For instance, the quantum theory of electromagnetism describes a vacuum devoid of particles such as photons, and each increment of energy added to this vacuum generates a new particle. In the quantum theory of gravity, a vacuum is the absence of spacetime—an emptiness so thorough we can scarcely imagine it. Loop gravity describes how each increment of energy added to this vacuum generates a new atom of spacetime.

The spacetime atoms form a dense, ever shifting mesh. Over large distances, their dynamism gives rise to the evolving universe of classical general relativity. Under ordinary conditions, we never notice the existence of these spacetime atoms; the mesh spacing is so tight that it looks like a continuum. But when spacetime is packed with energy, as it was at the big bang, the fine structure of spacetime becomes a factor, and the predictions of loop gravity diverge from those of general relativity.

[LOOP QUANTUM GRAVITY]

ATOMS OF SPACE

Relativity theory runs into trouble because it assumes space is a continuum. A more sophisticated theory, such as loop quantum gravity, holds that space is a mesh of tiny "atoms" (*spheres*). The diameter of these atoms (*lines*) is the so-called Planck length, the distance over which gravitational and quantum effects are comparable in strength.

Attracted to Repulsion

Applying the theory is an extremely complex task, so my colleagues and I use simplified versions that capture the truly essential features of the universe, such as its size, and ignore details of lesser interest. We have also had to adapt many of the standard mathematical tools of

SAMUEL VELASCO 5W *Infographics*

physics and cosmology. For instance, theoretical physicists commonly describe the world using differential equations, which specify the rate of change of physical variables, such as density, at each point in the spacetime continuum. But when spacetime is grainy, we instead use so-called difference equations, which break up the continuum into discrete intervals. These equations describe how a universe climbs up the ladder of sizes that it is allowed to take as it grows. When I set out to analyze the cosmological implications of loop gravity in 1999, most researchers expected that these difference equations would simply reproduce old results in disguise. But unexpected features soon emerged.

Gravity is typically an attractive force. A ball of matter tends to collapse under its own weight, and if its mass is sufficiently large, gravity overpowers all other forces and compresses the ball into a singularity, such as the one at the center of a black hole. But loop gravity suggests that the atomic structure of spacetime changes the nature of gravity at very high energy densities, making it repulsive. Imagine space as a sponge and mass and energy as water. The porous sponge can store water but only up to a certain amount. Fully soaked, it can absorb no more and instead repels water. Similarly, an atomic quantum space is porous and has a finite amount of storage space for energy. When energy densities become too large, repulsive forces come into play. The continuous space of general relativity, in contrast, can store a limitless amount of energy.

Because of the quantum-gravitational change in the balance of forces, no singularity—no state of infinite density—can ever arise. According to this model, matter in the early universe had a very high but finite density, the equivalent of a trillion suns in every proton-size region. At such extremes, gravity acted as a repulsive force, causing space to expand; as densities moderated, gravity switched to being the attractive force we all know. Inertia has kept the expansion going to the present day.

In fact, the repulsive gravity caused space to expand at an accelerating rate. Cosmological observations appear to require such an early period of acceleration, known as cosmic inflation. As the universe expands, the force driving inflation slowly subsides. Once the acceleration ends, surplus energy is transferred to ordinary matter, which begins to fill the universe in a process called reheating. In current models, inflation is somewhat ad hoc—added in to conform to observations—but in loop quantum cosmology, it is a natural consequence of the atomic nature of spacetime. Acceleration automatically occurs when the universe is small and its porous nature still quite significant.

Time before Time

Without a singularity to demarcate the beginning of time, the history of the universe may extend further back than cosmologists once thought possible. Other physicists have reached a similar conclusion [see "The Myth of the Beginning of Time," by Gabriele Veneziano; SCIENTIFIC AMERICAN, May 2004], but only rarely do their models fully resolve the singularity; most models, including those from string theory, require assumptions as to what might have happened at this uneasy spot. Loop gravity, in contrast, is able to trace what took place at the singularity. Loop-based scenarios, though admittedly simplified, are founded on general principles and avoid introducing new ad hoc assumptions.

Using the difference equations, we can try to reconstruct the deep past. One possible scenario is that the initial high-density state arose when a preexisting universe collapsed under the attractive force of gravity. The density grew so high that gravity switched to being repulsive, and the universe started expanding again. Cosmologists refer to this process as a bounce.

The first bounce model investigated thoroughly was an idealized case in which the universe was highly symmetrical and contained just one type

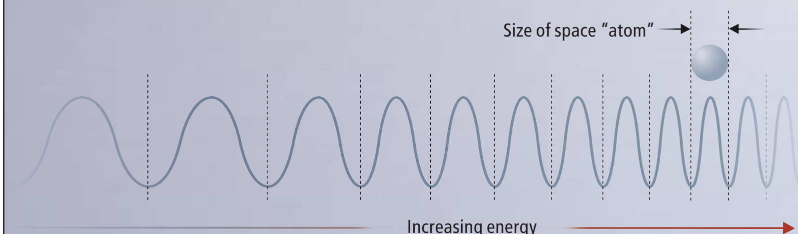
[THE AUTHOR]

Martin Bojowald is the leading researcher on the implications of loop quantum gravity for cosmology. He is a faculty member of the Institute for Gravitation and the Cosmos at Pennsylvania State University. Bojowald was awarded the First Award of the Gravity Research Foundation Essay Competition in 2003 and the Xanthopoulos Prize of the International Society for General Relativity and Gravitation in 2007. Outside physics, he enjoys reading classical literature and long-distance running in the Appalachian Mountains of central Pennsylvania.

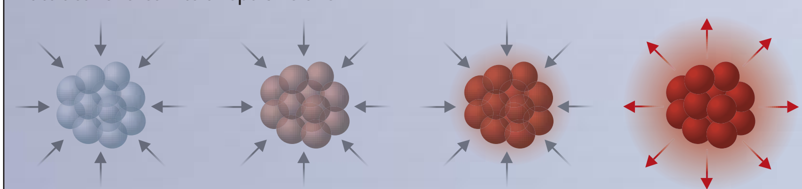
[WHAT SPACETIME ATOMS DO]

LOOKING QUITE REPULSIVE

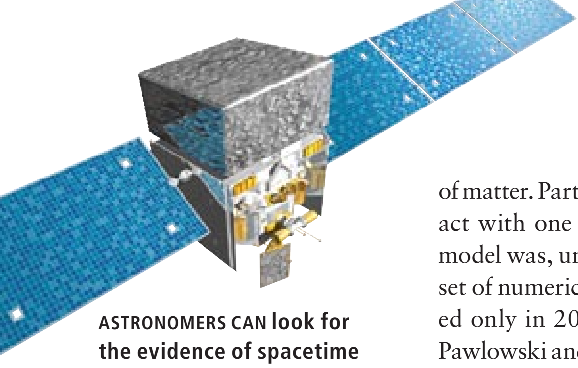
As you pack energy into a volume of space, the wavelength of particles carrying this energy shrinks and eventually approaches the size of the spacetime "atoms."



Space literally runs out of room. If you try to pack in still more energy, space will push it back out. It will appear that the gravity generated by the region has turned from an attractive force into a repulsive one.



FREDRIC WEBER *Pennsylvania State University (Bojowald)*; SAMUEL VELASCO *5W Infographics (illustrations)*



ASTRONOMERS CAN **look for the evidence of spacetime atoms, such as the analogues of random Brownian motion.**

of matter. Particles had no mass and did not interact with one another. Simplified though this model was, understanding it initially required a set of numerical simulations that were completed only in 2006 by Abhay Ashtekar, Tomasz Pawlowski and Parampreet Singh, all at Pennsylvania State University. They considered the propagation of waves representing the universe both before and after the big bang. The model clearly showed that a wave would not blindly follow the classical trajectory into the abyss of a singularity but would stop and turn back once the repulsion of quantum gravity set in.

An exciting result of these simulations was that the notorious uncertainty of quantum mechanics seemed to remain fairly muted during the bounce. A wave remained localized throughout the bounce rather than spreading out, as quantum waves usually do. Taken at face value, this result suggested that the universe before the bounce was remarkably similar to our own: governed by general relativity and perhaps filled with stars and galaxies. If so, we should be able to extrapolate from our universe back in time, through the bounce, and deduce what came before, much as we can reconstruct the paths of two billiard balls before a collision based on their paths after the collision. We do not need to know each and every atomic-scale detail of the collision.

Unfortunately, my subsequent analysis dashed this hope. The model as well as the quantum waves used in the numerical simulations turned out to be a special case. In general, I found that waves spread out and that quantum effects were strong enough to be reckoned with. So the bounce was not a brief push by a repulsive force, like the collision of billiard balls. Instead it may have represented the emergence of our universe from an almost unfathomable quantum state—a world in highly fluctuating turmoil. Even if the preexisting universe was once very similar to ours, it passed through an extended period during which the density of matter and energy fluctuated strongly and randomly, scrambling everything.

The fluctuations before and after the big bang were not strongly related to each other. The universe before the big bang could have been fluctuating very differently than it did afterward, and those details did not survive the bounce. The universe, in short, has a tragic case of forgetfulness. It may have existed before the big bang, but quantum effects during the bounce wiped out almost all traces of this prehistory.

Some Scraps of Memory

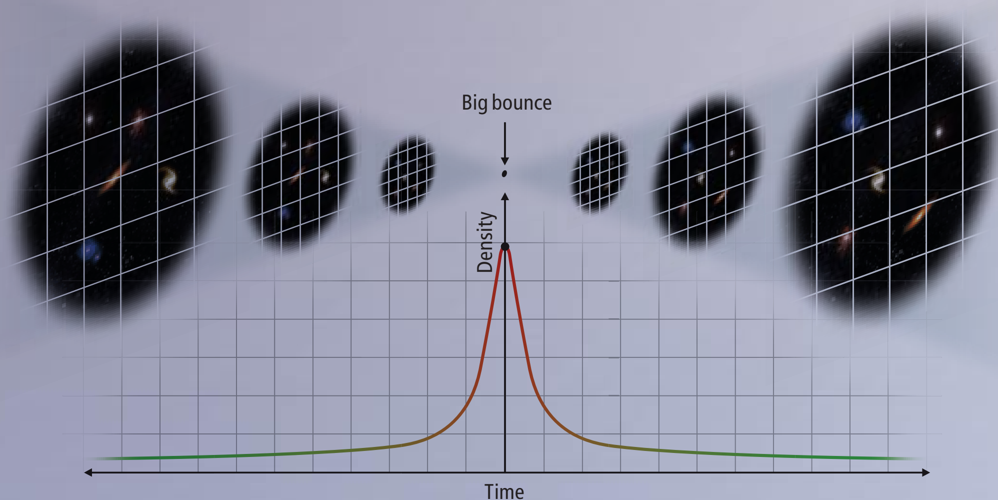
This picture of the big bang is subtler than the classical view of the singularity. Whereas general relativity simply fails at the singularity, loop quantum gravity is able to handle the extreme conditions there. The big bang is no longer a physical beginning or a mathematical singularity, but it does put a practical limitation on our knowledge. Whatever survives cannot provide a complete view of what came before.

SAMUEL VELASCO 5W Infographics (*big bang illustrations*); SLIM FILMS (*satellite*)

[A NEW VIEW OF COSMIC ORIGINS]

REPLACING THE BANG

By setting a limit to how much energy you can pack into space, loop quantum gravity replaces the big bang singularity with a big bounce—a process that looks like a beginning but actually reflects a transition from a preexisting state. The bounce sets the expansion of the universe in motion.



In one scenario, the universe is eternal. It imploded, reached the maximum allowable density (at the bounce), and blew apart again.

Frustrating as this may be, it might be a conceptual blessing. In physical systems as in daily life, disorder tends to increase. This principle, known as the second law of thermodynamics, is an argument against an eternal universe. If order has been decreasing for an infinite span of time, the universe should by now be so disorganized that structures we see in galaxies as well as on Earth would be all but impossible. The right amount of cosmic forgetfulness may come to the rescue by presenting the young, growing universe with a clean slate irrespective of all the mess that may have built up before.

According to traditional thermodynamics, there is no such thing as a truly clean slate; every system always retains a memory of its past in the configuration of its atoms [see "The Cosmic Origins of Time's Arrow," by Sean M. Carroll; Scientific American, June]. But by allowing the number of spacetime atoms to change, loop quantum gravity allows the universe more freedom to tidy up than classical physics would suggest.

All that is not to say that cosmologists have no hope of probing the quantum-gravitational period. Gravitational waves and neutrinos are especially promising tools, because they barely interact with matter and therefore penetrated the primordial plasma with minimal loss. These messengers might well bring us news from a time near to, or even before, the big bang.

One way to look for gravitational waves is by studying their imprint on the cosmic microwave background radiation [see "Echoes from the Big Bang," by Robert R. Caldwell and Marc Kamionkowski; Scientific American, January 2001]. If quantum-gravitational repulsive gravity drove cosmic inflation, these observations might find some hint of it. Theorists must also determine whether this novel source of inflation could reproduce other cosmological measurements, especially of the early density distribution of matter seen in the cosmic microwave background.

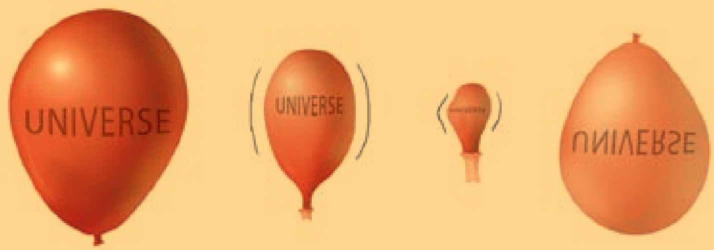
At the same time, astronomers can look for the spacetime analogues of random Brownian motion. For instance, quantum fluctuations of spacetime could affect the propagation of light over long distances. According to loop gravity, a light wave cannot be continuous; it must fit on the lattice of space. The smaller the wavelength, the more the lattice distorts it. In a sense, the spacetime atoms buffet the wave. As a consequence, light of different wavelengths travels at different speeds. Although these differences are tiny, they may add up during a long trip. Distant sources such as gamma-ray bursts offer the best hope of seeing this effect [see "Window on the Extreme Universe," by William B. Atwood, Peter F. Michelson and Steven Ritz; Scientific American, December 2007].

In the case of material atoms, more than 25 centuries elapsed between the first speculative suggestions of atoms by ancient philosophers and Einstein's analysis of Brownian motion, which firmly established atoms as the subject of experimental science. The delay should not be as long for spacetime atoms. ■

Mirror, Mirror

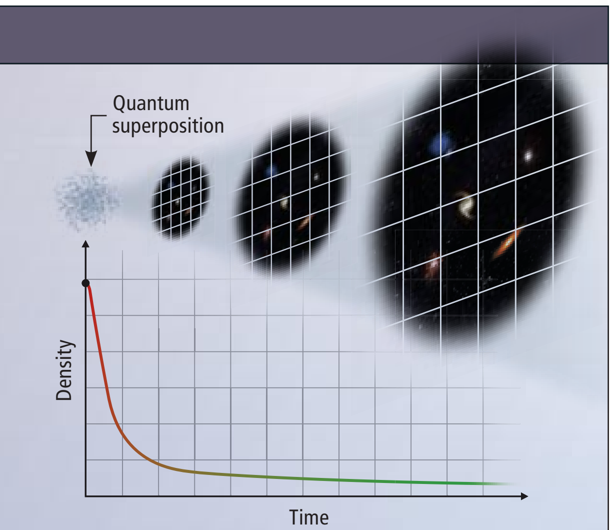
Despite the effects that scrambled the universe during the big bounce, physicists can make some educated guesses about what came before. Some are truly strange. For instance, the difference equations of loop quantum gravity imply that the region of spacetime preceding the bounce was a mirror image of space in our universe. That is, what was right-handed after the bang was left-handed before, and vice versa.

To visualize this effect, imagine a deflating balloon that, instead of settling down to a limp piece of rubber, preserves its energy and momentum. The rubber, once set in motion, tends to stay in motion. So, as the balloon collapses down to a minimum size, it turns inside out and starts growing again. What was previously the outside of the balloon becomes the inside, and vice versa. Similarly, when spacetime atoms cross one another at the big bounce, the universe turns inside out.



This reversal is interesting because elementary particles are not perfectly mirror-symmetric; certain processes change when the orientation does. This asymmetry has to be taken into account to understand what happens to matter at the bounce. *—M.B.*

LILA RUBENSTEIN (*balloons*)



Alternatively, before the big bounce the universe may have been in an almost unimaginable quantum state, not yet spacelike, when something triggered the big bounce and the formation of the atoms of spacetime. Which of these two alternatives occurred depends on further details that physicists are still working out.

MORE TO EXPLORE

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What Happened before the Big Bang? Martin Bojowald in *Nature Physics,* Vol. 3, No. 8, pages 523–525; August 2007.

Loop Quantum Cosmology. Martin Bojowald in *Living Reviews in Relativity,* Vol. 11, No. 4; July 2, 2008. Available at **http://relativity.livingreviews.org/Articles/lrr-2008-4**

LIGHTING UP THE BRAIN

A clever combination of optics and genetics is allowing neuroscientists to map—and even control—brain circuits with unprecedented precision

By Gero Miesenböck

KEY CONCEPTS

- Neuroscientists have traditionally studied the function of the brain by stimulating and recording the activity of single nerve cells with electrodes. But this method is indirect, making analyses of specific neurons very difficult.
- The emerging field of optogenetics, which combines genetic engineering with light to observe and control groups of neurons, is allowing researchers to scrutinize individual neural circuits—an approach that will revolutionize the study of brain function.

—The Editors

In 1937 the great neuroscientist Sir Charles Scott Sherrington of the University of Oxford laid out what would become a classic description of the brain at work. He imagined points of light signaling the activity of nerve cells and their connections. During deep sleep, he proposed, only a few remote parts of the brain would twinkle, giving the organ the appearance of a starry night sky. But at awakening, "it is as if the Milky Way entered upon some cosmic dance," Sherrington reflected. "Swiftly the head-mass becomes an enchanted loom where millions of flashing shuttles weave a dissolving pattern, always a meaningful pattern though never an abiding one; a shifting harmony of subpatterns."

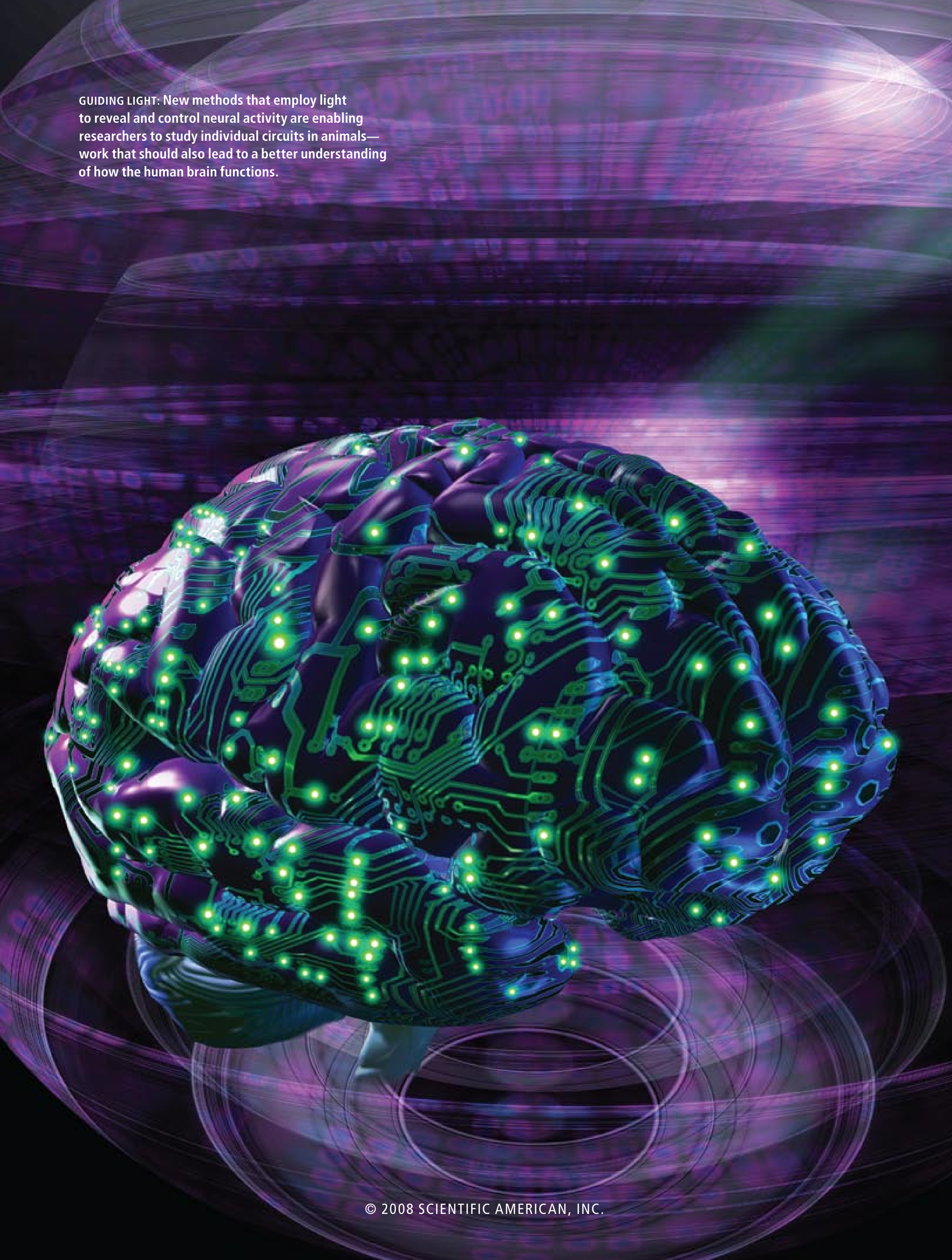
Although Sherrington probably did not realize it at the time, his poetic metaphor contained an important scientific idea: that of the brain revealing its inner workings optically. Understanding how neurons work together to generate thoughts and behavior remains one of the most difficult open problems in all of biology, largely because scientists generally cannot see whole neural circuits in action. The standard approach of probing one or two neurons with electrodes reveals only tiny fragments of a much bigger puzzle, with too many pieces missing to guess the full picture. But if one could watch neurons communicate, one might be able to deduce how brain circuits are laid out and how they function. This alluring notion has inspired neuroscientists to attempt to realize Sherrington's vision.

Their efforts have given rise to a nascent field called optogenetics, which combines genetic engineering with optics to study specific cell types. Already investigators have succeeded in visualizing the functions of various groups of neurons. Furthermore, the approach has enabled them to actually control the neurons remotely—simply by toggling a light switch. These achievements raise the prospect that optogenetics might one day lay open the brain's circuitry to neuroscientists and perhaps even help physicians to treat certain medical disorders.

Enchanting the Loom

Attempts to turn Sherrington's vision into reality began in earnest in the 1970s. Like digital computers, nervous systems run on electricity; neurons encode information in electrical signals, or action potentials. These impulses, which typically involve voltages less than a tenth of those

ALFRED T. KAMAJIAN



GUIDING LIGHT: New methods that employ light to reveal and control neural activity are enabling researchers to study individual circuits in animals—work that should also lead to a better understanding of how the human brain functions.

of a single AA battery, induce a nerve cell to release neurotransmitter molecules that then activate or inhibit connected cells in a circuit. In an effort to make these electrical signals visible, Lawrence B. Cohen of Yale University tested a large number of fluorescent dyes for their ability to respond to voltage changes with changes in color or intensity. He found that some dyes indeed had voltage-sensitive optical properties. By staining neurons with these dyes, Cohen could observe their activity under a microscope.

Dyes can also reveal neural firing by reacting not to voltage changes but to the flow of specific charged atoms, or ions. When a neuron generates an action potential, membrane channels open and admit calcium ions into the cell. This calcium influx stimulates the release of neurotransmitters. In 1980 Roger Y. Tsien, now at the University of California, San Diego, began to synthesize dyes that could indicate shifts in calcium concentration by changing how brightly they fluoresced. These optical reporters have proved extraordinarily valuable, opening new windows on information processing in single neurons and small networks.

Synthetic dyes suffer from a serious drawback, however. Neural tissue is composed of many different cell types. Estimates suggest that the brain of a mouse, for example, houses many hundreds of types of neurons plus numerous kinds of support cells. Because interactions between specific types of neurons form the basis of neural information processing, someone who wants to understand how a particular circuit works must be able to identify and monitor the individual players and pinpoint when they turn on (fire an action potential) and off. But because synthetic dyes stain all cell types indiscriminately, it is generally impossible to trace the optical signals back to specific types of cells.

[THE AUTHOR]

Gero Miesenböck recently moved from Yale University to the University of Oxford, where he is Waynflete Professor of Physiology. This is the post Charles Sherrington, one of the founders of modern neuroscience, held from 1913 until his retirement in 1935.

Genes and Photons

Optogenetics emerged from the realization that genetic manipulation might be the key to solving this problem of indiscriminate staining. An individual's cells all contain the same genes, but what makes two cells different from each other is that different mixes of genes get turned on or off in them. Neurons that release the neurotransmitter dopamine when they fire, for instance, need the enzymatic machinery for making and packaging dopamine. The genes encoding the protein components of this machinery are thus switched on in dopamine-producing (dopaminergic) neurons but stay off in other, nondopaminergic neurons.

In theory, if a biological switch that turned a dopamine-making gene on was linked to a gene encoding a dye and if the switch-and-dye unit were engineered into the cells of an animal, the animal would make the dye only in dopaminergic cells. If researchers could peer into the brains of these creatures (as is indeed possible), they could see dopaminergic cells functioning in virtual isolation from other cell types. Furthermore, they could observe these cells in the intact, living brain. Synthetic dyes cannot perform this type of magic, because their production is not controlled by genetic switches that flip to on exclusively in certain kinds of cells. The trick works only when a dye is encoded by a gene—that is, when the dye is a protein.

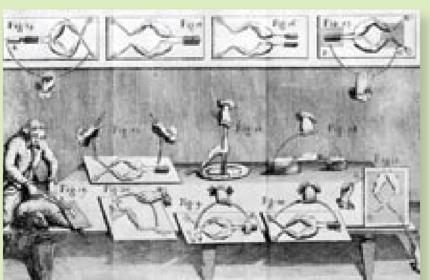
The first demonstrations that genetically encoded dyes could report on neural activity came

PHIL SAYER (*Miesenböck*); TIME & LIFE PICTURES/GETTY IMAGES (*Galvani experiment*); LIBRARY OF CONGRESS/PHOTO RESEARCHERS, INC. (*Sherrington*); COURTESY OF JOSÉ DELGADO (*bull in ring*)

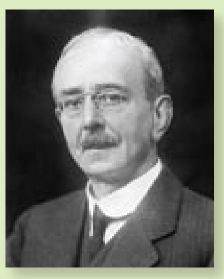
[HISTORY]

DECODING THE BRAIN

Scientists have long endeavored to uncover how the nervous system gives rise to behavior. Early efforts to stimulate and visualize neural activity laid the groundwork for the emergence of optogenetics.



1783: Italian anatomist Luigi Galvani uses electricity to make a dead frog's leg twitch



1937: British neuroscientist Charles Sherrington envisions points of light signaling neural activity

1963: Spanish physiologist José Delgado uses radio waves to halt a charging bull

1971: Fluorescent voltage-sensitive dyes make their debut

1980: Fluorescent dyes that reveal changes in calcium concentration in a cell are synthesized

1700 | 1930 | 1940 | 1950 | 1960 | 1970 | 1980

a decade ago, from teams led independently by Tsien, Ehud Y. Isacoff of the University of California, Berkeley, and me, with James E. Rothman, now at Yale University. In all cases, the gene for the dye was borrowed from a luminescent marine organism, typically a jellyfish that makes the so-called green fluorescent protein. We tweaked the gene so that its protein product could detect and reveal the changes in voltage or calcium that underlie signaling within a cell, as well as the release of neurotransmitters that enable signaling between cells.

Armed with these genetically encoded activity sensors, we and others bred animals in which the genes encoding the sensors would turn on only in precisely defined sets of neurons. Many favorite organisms of geneticists—including worms, zebra fish and mice—have now been analyzed in this way, but fruit flies have proved particularly willing to spill their secrets under the combined assault of optics and genetics. Their brains are compact and visible through a microscope, so entire circuits can be seen in a single field of view. Furthermore, flies are easily modified genetically, and a century of research has identified many of the genetic on-off switches necessary for targeting specific groups of neurons. Indeed, it was in flies that Minna Ng, Robert D. Roorda and I, all of us then at Memorial Sloan-Kettering Cancer Center in New York City, recorded the first images of information flow between defined sets of neurons in an intact brain. We have since discovered new circuit layouts and new operating principles. For example, last year we found neurons in the fly's scent-processing circuitry that appear to inject "background noise" into the system. We speculate that the added buzz amplifies faint inputs, thus heightening the animal's sensitivity to smells—all the better for finding food.

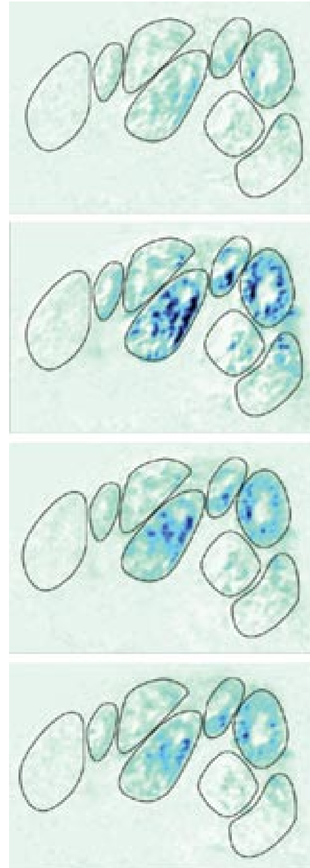
The sensors provided us with a powerful tool for observing communication among neurons. But back in the late 1990s we still had a problem. Most experiments probing the function of the nervous system are rather indirect. Investigators stimulate a response in the brain by exposing an animal to an image, a tone or a scent, and they try to work out the resulting signaling pathway by inserting electrodes at downstream sites and measuring the electrical signals picked up at these positions. Unfortunately, sensory inputs undergo extensive reformatting as they travel. Consequently, knowing exactly which signals underlie responses recorded at some distance from the eye, ear or nose becomes harder the farther one moves from these organs. And, of course, for the many circuits in the brain that are not devoted to sensory processing but rather to movement, thought or emotion, the approach fails outright: there is no direct way of activating these circuits with sensory stimuli.

From Observation to Control

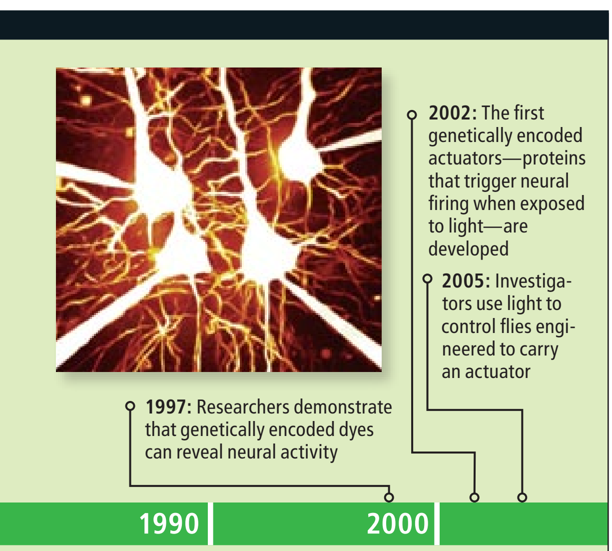
An ability to stimulate specific groups of neurons directly, independent of external input to sensory organs, would alleviate this problem. We wondered, therefore, if we could develop a package of tools that would not only provide sensors to monitor the activity of nerve cells but would also make it possible to readily activate only selected neuron types.

My first postdoctoral fellow, Boris V. Zemelman, now at the Howard Hughes Medical Institute, and I took on this problem. We knew that if we managed to program a genetically encoded, light-controlled actuator, or trigger, into neurons, we could overcome several obstacles that had impeded electrode-based studies of neural circuits. Because only a limited number of electrodes can be implanted in a test subject simultaneously, researchers can listen to or excite only a small number of cells at any given time using this approach. In addition, electrodes are difficult to aim at specific cell types. And they must stay put, encumbering experiments in mobile animals.

If we could tap a genetic on-off switch to help us find all the relevant neurons (those producing dopamine, for instance) and if we could use light to control these cells in a hands-off manner, we would no longer have to know in advance where in the brain these neurons were located to study



OPTICAL EAVESDROPPING: By outfitting neurons with molecular sensors that emit light when those cells are activated, neuroscientists can track information processing as it is happening in neural circuits. The sequence of video frames above, for instance, tracked the activity of odor-sensing neurons that impinge on specific areas (*circled*) of a fly's brain. Excitation of the neurons led to an increase in fluorescence (*blue spots*), which then subsided as the cells quieted down.



JESPER SJÖSTRÖM AND MICHAEL HÄUSSER *University College London (pyramidal neurons)*; GERO MIESENBÖCK; FROM "VIDEO-RATE NONLINEAR MICROSCOPY OF NEURONAL MEMBRANE DYNAMICS WITH GENETICALLY ENCODED PROBES," BY ROBERT D. ROORDA, TOBIAS M. HOHL, RICARDO TOLEDO-CROW AND GERO MIESENBÖCK, IN *JOURNAL OF NEUROPHYSIOLOGY*, VOL. 92; MARCH 3, 2004 (*fluorescence video sequence*)

THE E

ONE OF MANKIND'S BIGGEST CHALLENGES IS TO MAKE OUR WORLD WORK IN A WAY THAT SUSTAINS
SOME CALL IT ENGINEERING. WE CALL IT CREATIVE PROBLEM-SOLVING. REAL


NGINE
EVERYTHING THAT IS WONDERFUL ABOUT THIS PLANET. TO DO SO WILL TAKE A SPECIAL KIND OF SKILL.
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them. And it would not matter if their positions changed as an animal moved about. If stimulation of cells containing the actuators evoked a behavioral change, we would know that these cells were operating in the circuit regulating that behavior. At the same time, if we arranged for those same cells to carry a sensor gene, the active cells would light up, revealing their location in the nervous system. Presumably, by rerunning the experiment repeatedly on animals engineered to each have a different cell type containing an actuator, we would eventually be able to piece together the sequence of events leading from neural excitation to behavior and to identify all the players in the circuit. All we needed to do was discover a genetically encodable actuator that could transduce a light flash into an electrical impulse.

To find such an actuator, we reasoned that we should look in cells that normally generate electrical signals in response to light, such as the photoreceptors in our eyes. These cells contain light-absorbing antennae, termed rhodopsins, that when illuminated instruct ion channels in the cell membrane to open or close, thereby altering the flow of ions and producing electrical signals. We decided to transplant the genes encoding these rhodopsins (plus some auxiliary genes required for rhodopsin function) into neurons grown in a petri dish. In this simple setting we could then test whether shining light onto the dish would cause the neurons to fire. Our experiment worked—in early 2002, four years after the development of the first genetically encoded sensors able to report neural activity, the first genetically encoded actuators debuted.

Remote-Controlled Flies

More recently, investigators have enlisted other light-sensing proteins, such as melanopsin, which is found in specialized retinal cells that help to synchronize the circadian clock to the earth's rotation, as actuators. And the combined efforts of Georg Nagel of the Max Planck Institute for Biophysics in Frankfurt, Karl Deisseroth of Stanford University and Stefan Herlitze of Case Western Reserve University have shown that another protein, called channelrhodopsin-2—which orients the swimming movements of algae—is up to the job. There are also a variety of genetically encoded actuators that can be controlled via light-sensitive chemicals synthesized by us and by Isacoff and his U.C. Berkeley colleagues Richard H. Kramer and Dirk Trauner.

The next step was to demonstrate that our actuator could work in a living animal, a challenge I posed to my first graduate student, Susana Q. Lima. To obtain this proof of principle, we focused on a particularly simple circuit in flies, one consisting of just a handful of cells. This circuit was known to control an unmistakable behavior: a dramatic escape reflex by which the insect rapidly extends its legs to achieve liftoff and, once airborne, spreads its wings and flies. The trigger initiating this action sequence is an electrical impulse emitted by two of the roughly 150,000 neurons in the fly's brain. These so-called command neurons activate a subordinate circuit called a pattern generator that instructs the muscles moving the fly's legs and wings.

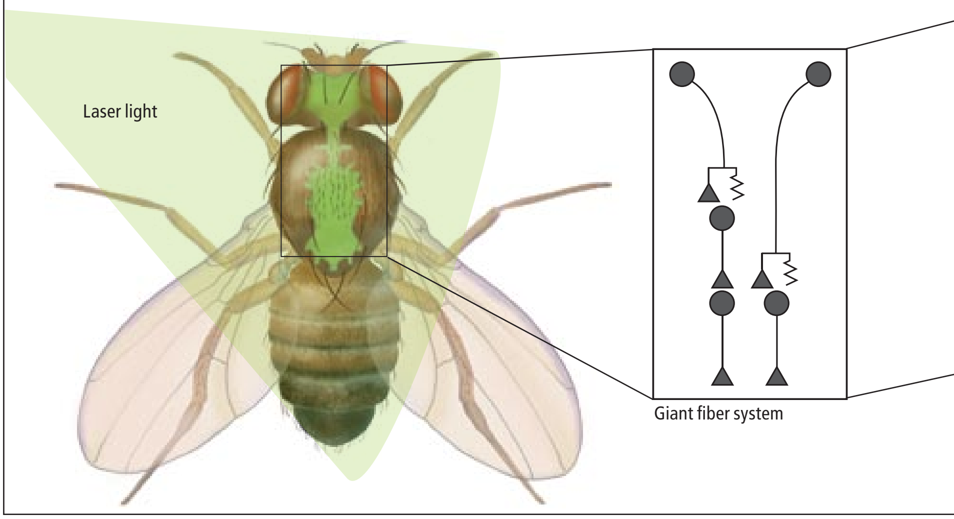
We found a genetic switch that was always on in the two command neurons but no others—and another switch that was on in neurons of the pattern generator but not in the command neurons. Using these switches, we engineered flies in which either the command neurons or the pattern-generator neurons produced our light-driven actuator. To our delight, both kinds of flies took off at the flash of a laser beam, which was strong enough to penetrate the cuticle of the intact animals and reach the nervous system. This confirmed that both the command and pattern-generating cells participated in the escape reflex and proved that the actuators worked as intended. Because only the relevant neurons contained the genetically encoded ac-

To our delight, both kinds of flies took off at the flash of a laser beam.

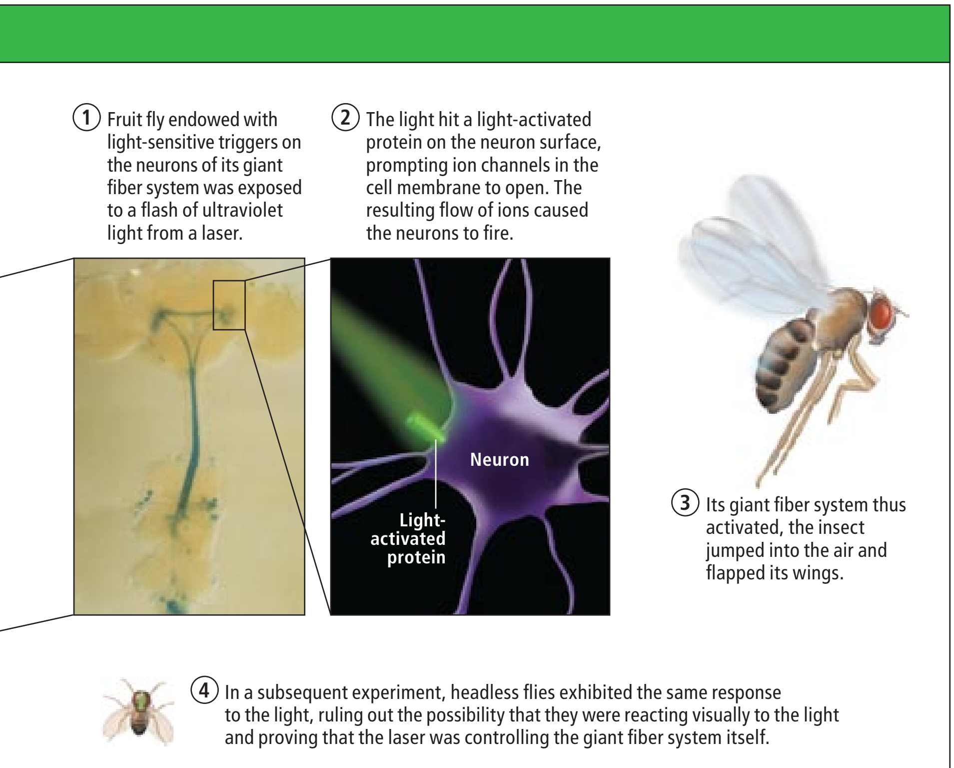
[PROOF-OF-CONCEPT EXPERIMENT]

REMOTE-CONTROLLING A FLY

Proof that light-sensitive proteins could work as actuators—scientist-controlled "on switches"—in the neurons of living animals came from experiments with fruit flies. The flies were engineered so that only the neurons in their so-called giant fiber system made the proteins. These neurons have long been known to trigger the insect's escape response when activated. In the experiment depicted below, exposing the fly's nervous system to a flash of ultraviolet light elicited this escape response, indicating that the actuator worked as intended.



LILA RUBENSTEIN (*all drawings*); FROM "MUTATIONS IN *SHAKING-B* PREVENT ELECTRICAL SYNAPSE FORMATION IN THE *DROSOPHILA* GIANT FIBER SYSTEM," BY PAULINE PHELAN ET AL., IN *JOURNAL OF NEUROSCIENCE*, VOL. 16, NO. 3; FEBRUARY 1, 1996 (*stained giant fiber system*)

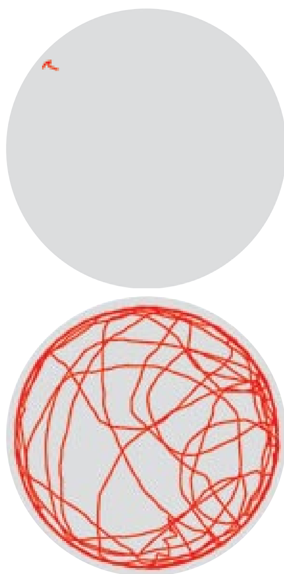


tuator, they alone "knew" to respond to the optical stimulus—we did not have to aim the laser at specific target cells. It was as if we were broadcasting a radio message over a city of 150,000 homes, only a handful of which possessed the receiver required to decode the signal; the message remained inaudible to the rest.

One nagging quandary remained, however. The command neurons initiating the escape reflex are wired to inputs from the eyes. These inputs activate the escape circuit during a "lights-off" transition, as happens when a looming predator casts its shadow. (You know this from your fly-swatting attempts: whenever you move your hand into position, the animal annoyingly jumps up and flies away.) We worried that in our case, too, the escape reflex might be a visual reaction to the laser pulse, not the result of direct optical control of command or pattern-generating circuits.

To eliminate this concern, we performed a brutally simple experiment: we cut the heads off our flies. This left us with headless drones (which can survive for a day or two) that harbored the intact pattern-generating circuitry within their thoracic ganglia, which form the rough equivalent of a vertebrate's spinal cord. Activating this circuit with light propelled the otherwise motionless bodies into the air. Although the drones' flights often began with tumbling instability and ended in spectacular crashes or collisions, their very existence proved that the laser controlled the pattern-generating circuit itself—there was no other way these headless animals could detect and react to light. (The drones' clumsy maneuvers also illustrated vividly that the Wright brothers' great innovation was the invention of controlled powered flight, not simply powered flight.)

We also engineered flies with light switches attached only to neurons that make the neurotransmitter dopamine. When exposed to the laser's flash, these flies suddenly became more active, walking all around their enclosures. Previous studies had indicated that dopamine helps animals predict reward and punishment. Our fly findings are consistent with this scenario: the animals not only became more active, they also explored their environment differently, as if reacting to an altered expectation of gain or loss.



ACTIVITY PATTERNS of fruit flies whose dopamine-producing neurons were engineered to be photosensitive changed dramatically when the animals were strobed with light. The flies went from barely moving (*top*) to inspecting their enclosures in detail (*bottom*), bolstering the theory that dopamine increases exploratory behavior.

An Unexpected Forerunner

Three days before the paper reporting these experiments was scheduled for publication in the journal *Cell,* I was flying to Los Angeles to deliver a lecture. A friend had given me Tom Wolfe's recently published coming-of-age novel *I Am Charlotte Simmons,* thinking I would enjoy its depiction of neuroscientists, not to mention the material that had earned the book the *Literary Review*'s Bad Sex in Fiction Award. On the plane I came across a passage in which Charlotte attends a lecture on the work of one José Delgado, who also remotely controls animal behavior—not with light-driven, genetically encoded actuators but with radio signals transmitted to electrodes he has implanted in the brain. A Spaniard, Delgado risked his life to demonstrate the power of his approach by stopping an angry bull in midcharge. This, Wolfe's fictional lecturer declares, is a turning point in neuroscience—a decisive defeat of dualism, the notion that the mind exists as an entity separate from the brain. If Delgado's physical manipulations of the brain could change an animal's mind, so the argument went, the two must be one and the same.

I almost fell out of my seat. Was Delgado a fictional character, or was he real? Immediately after landing in L.A., I did a Web search and was directed to a photograph of the matador with the remote and his bull. Delgado, I learned, had been a professor at my very own institution, Yale, and had written a book entitled *Physical Control of the Mind: Toward a Psychocivilized Society,* which appeared in 1969. In it, he sum-

marized his efforts to control movements, evoke memories and illusions, and elicit pleasure or pain [see "The Forgotten Era of Brain Chips," by John Horgan; SCIENTIFIC AMERICAN, October 2005]. The book concludes with a discussion of what the ability to control brain function might imply for medicine, ethics, society and even warfare. Against this background, I should probably not have been surprised when the phone rang the day our paper was published and a U.S.-based journalist asked, "So, when are we going to invade another country with an army of remote-controlled flies?"

[OTHER OPTOGENETICS EXPERIMENTS]

MAKING SENSE OF CIRCUITS

Recent studies employing optogenetic techniques have enabled neuroscientists to locate and manipulate neural circuits governing a number of behaviors in flies, worms, fish and mice. Here are just a few examples of what they learned.

	ANIMAL	BEHAVIOR STUDIED	WHAT WAS LEARNED
Visualization Experiments	Fruit fly	Olfactory memory	So-called dorsal paired medial neurons form a feedback circuit for stabilizing memories related to odor
Visualization Experiments	Roundworm	Food seeking	Removal of food causes persistent activity in neurons known as AWC; this activity alters the worm's search strategy
Visualization Experiments	Mouse	Gender recognition	The ability to recognize gender is encoded by dedicated male- and female-specific pheromone-sensing cells
	ANIMAL	BEHAVIOR STUDIED	WHAT WAS LEARNED
Remote-Control Experiments	Fruit fly	Stress avoidance	Carbon dioxide released by stressed flies triggers an avoidance response in other flies
Remote-Control Experiments	Zebra fish	Escape	The escape reflex to touch can be turned on and off by sensory inputs
Remote-Control Experiments	Mouse	Decision making	Perceptual decisions are influenced by electrical activity in fewer than 300 cortical neurons

The media attention did not stop there. The next day the headline of the Drudge Report screamed, "Scientists Create Remote-Controlled Flies," topping news of Michael Jackson's latest court appearance. I assume it was this source that inspired a sketch on the *Tonight Show* a week or so later, in which host Jay Leno piloted a remote-controlled fly into President George W. Bush's mouth—the first practical application of our new technology.

Since then, researchers have used the light-switch approach to control other behaviors. Last October, Deisseroth and his Stanford colleague Luis de Lecea announced the results of a mouse study in which they used an optical fiber to deliver light directly to neurons that produce hypocretin—a neurotransmitter in the form of a small protein, or peptide—to see whether these neurons regulate sleep. Researchers had suspected that hypocretin plays this role because certain breeds of dogs lacking hypocretin receptors suffer sudden bouts of sleepiness. The new work revealed that stimulating hypocretin neurons during sleep tended to awaken the mice, bolstering that hypothesis.

And in my lab at Yale, postdoctoral fellow J. Dylan Clyne used genetically encoded actuators to gain insights into behavioral differences between the sexes. The males of many animal species go to considerable lengths in wooing the opposite sex. In the case of fruit flies, males vibrate one wing to produce a "song" that females find quite irresistible. To probe the neural underpinnings of this strictly male behavior, Clyne used light to activate the pattern generator responsible for the song. He found that females, too, possess the song-making circuitry. But under normal circumstances they lack the neural signals required for turning it on. This discovery suggests that male and female brains are wired largely the same way and that differences in sexual behaviors arise from the action of strategically placed master switches that set circuits to either male or female mode.

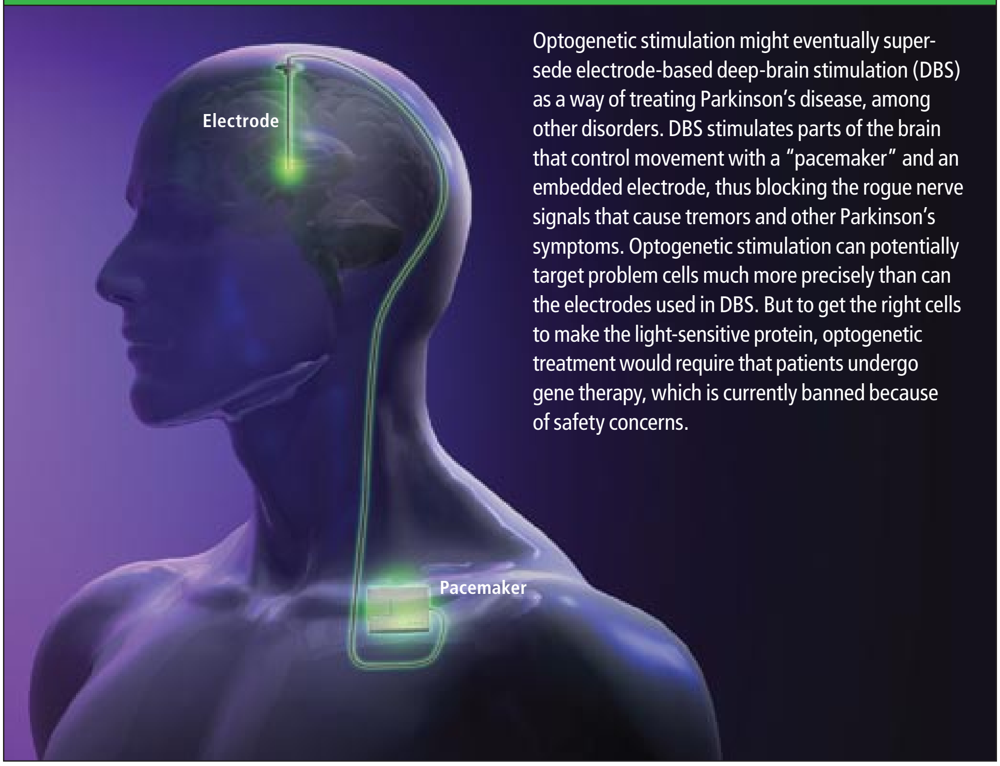
Light Therapy

Thus far investigators have typically engineered animals to carry either a sensor or an actuator in neurons of interest. But it is possible to outfit them with both. And down the road, the hope is that we will be able to breed subjects that have multiple sensors or actuators, which would allow us to study assorted populations of neurons simultaneously in the same individual.

Our newfound authority over neural circuits

[APPLICATION]

THERAPEUTIC POTENTIAL



Optogenetic stimulation might eventually supersede electrode-based deep-brain stimulation (DBS) as a way of treating Parkinson's disease, among other disorders. DBS stimulates parts of the brain that control movement with a "pacemaker" and an embedded electrode, thus blocking the rogue nerve signals that cause tremors and other Parkinson's symptoms. Optogenetic stimulation can potentially target problem cells much more precisely than can the electrodes used in DBS. But to get the right cells to make the light-sensitive protein, optogenetic treatment would require that patients undergo gene therapy, which is currently banned because of safety concerns.

ALFRED T. KAMAJIAN

is creating enormous opportunities for basic research. But are there practical benefits? Perhaps, although I feel they are sometimes overhyped. Delgado himself identified several areas in which direct control of neural function could lead to clinical benefits: sensory prosthetics, therapy for movement disorders (as has now become reality with deep-brain stimulation for Parkinson's disease), and regulation of mood and behavior. He saw these potential uses as a direct and rational extension of existing medical practice, not as an alarming foray into the ethical quicksands of "mind control." Indeed, it would seem arbitrary and hypocritical to draw a sharp boundary between physical means for influencing brain function and chemical manipulations, be they psychoactive pharmaceuticals or the cocktail that helps you unwind after a hard day. In fact, physical interventions can arguably be targeted and dosed more precisely than drugs, thus reducing side effects.

Some studies have already begun to probe the applicability of optogenetics to medical problems. In 2006 researchers used light-activated ion channels to restore photosensitivity to surviving retinal neurons in mice with photoreceptor degeneration. They used a virus to deliver the gene encoding channelrhodopsin-2 to the cells, injecting it directly into the animals' eyes. The patched-up retinas sent light-evoked signals to the brain, but whether the procedure actually brought back vision remains unknown.

Despite their theoretical appeal, optogenetic therapies face an important practical obstacle in humans: they require the introduction of a foreign gene—the one encoding the light-controlled actuator—into the brain. So far gene therapy technology is not up to the challenge, and the Food and Drug Administration is sufficiently concerned about the associated risks that it has banned such interventions for the time being, except for tightly restricted experimental purposes.

The immediate opportunity afforded by our control over brain circuits—or even other electrically excitable cells, such as those that produce hormones and those that make up muscle—lies in revealing new targets for drugs: if experimental manipulations of cell groups X, Y and Z cause an animal to eat, sleep or throw caution to the wind, then X, Y and Z are potential targets for medicines against obesity, insomnia and anxiety, respectively. Finding compounds that regulate neurons X, Y and Z may well lead to new or better treatments for disorders that have no therapies at the moment or to new uses for existing drugs. Much remains to be discovered, but the future of optogenetics shines brightly. ■

MORE TO EXPLORE

Transmission of Olfactory Information between Three Populations of Neurons in the Antennal Lobe of the Fly. Minna Ng, Robert D. Roorda, Susana Q. Lima, Boris V. Zemelman, Patrick Morcillo and Gero Miesenböck in *Neuron,* Vol. 36, No. 3, pages 463–474; 2002.

Remote Control of Behavior through Genetically Targeted Photostimulation of Neurons. Susana Q. Lima and Gero Miesenböck in *Cell,* Vol. 121, No. 1, pages 141–152; 2005.

Neural Substrates of Awakening Probed with Optogenetic Control of Hypocretin Neurons. Antoine R. Adamantidis, Feng Zhang, Alexander M. Aravanis, Karl Deisseroth and Luis de Lecea in *Nature,* Vol. 450, pages 420–424; 2007.

Sex-Specific Control and Tuning of the Pattern Generator for Courtship Song in *Drosophila.* J. Dylan Clyne and Gero Miesenböck in *Cell,* Vol. 133, No. 2, pages 354–363; 2008.

AFAR DEPRESSION marks the north end of the East African Rift, a 3,500-kilometer-long zone of tectonic turmoil that is tearing the continent in two (*arrows on globe*). The detail above shows a segment of the depression.

KEVIN HAND (*maps*)

Birth of an Ocean

Story and photographs by Eitan Haddok

GHOSTLY SALT DEPOSITS near Afdera volcano testify to ancient inundations in Ethiopia's Afar region. In the past 200,000 years the Red Sea flooded Afar's lowlands at least three times; the salt stayed behind as the seawater evaporated. One day the ersatz seascape will likely become the real thing.

Formation of an ocean is a rare event, one few scientists have ever witnessed. Yet this geophysical nativity is unfolding today in one of the hottest and most inhospitable corners of the globe. Visit the site in safety through this extraordinary photographic essay

KEY CONCEPTS

- Africa is splitting apart at the seams—literally. From the southern tip of the Red Sea southward through Eritrea, Ethiopia, Kenya, Tanzania and Mozambique, the continent is coming unstitched along a zone called the East African Rift.
- Like a shirtsleeve tearing under a bulging bicep, the earth's crust rips apart as molten rock from deep down pushes up on the solid surface and stretches it thin—sometimes to its breaking point. Each new slit widens as lava fills the gap from below.
- This spectacular geologic unraveling, already under way for millions of years, will be complete when saltwater from the Red Sea floods the massive gash. Ten million years from now the entire rift may be submerged.

—The Editors

In northeastern Ethiopia one of the earth's driest deserts is making way for a new ocean. This region of the African continent, known to geologists as the Afar Depression, is pulling apart in two directions—a process that is gradually thinning the earth's rocky outer skin. The continental crust under Afar is a mere 20 kilometers from top to bottom, less than half its original thickness, and parts of the area are over 100 meters below sea level. Low hills to the east are all that stops the Red Sea from encroaching.

Such proximity to the planet's scorching interior has transformed the region into a dynamic landscape of earthquakes, volcanoes and hydrothermal fields—making Afar a veritable paradise for people, like me, eager to understand those processes. Yet few outsiders, scientists included, have ever set foot in Afar. Daytime temperatures soar to 48 degrees Celsius (118 degrees Fahrenheit) in the summer, and no rain falls for much of the year. But I knew I faced more than treacherous geology and climate. Nasty geopolitical struggles—namely, war between Ethiopia and neighboring Eritrea—combine with those natural hardships to make Afar utterly inhospitable.

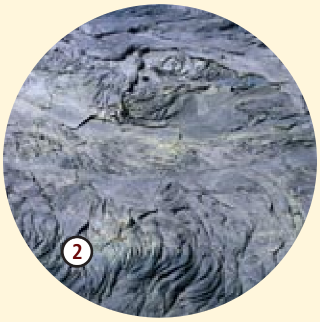
Geologists predict another million years of the land stretching and sinking, combined with a massive deluge from the Red Sea, could put Afar at the bottom of a new ocean. For now, this incipient seabed is a desolate landscape where lava stifles vegetation, hellish heat makes acid boil, devilish formations emit toxic fumes, and the salty legacy of ancient Red Sea floods provides nomadic tribes of Afar with a precious export.

RISING ABOVE

The highest point in sunken Afar is Erta Ale, or "smoking mountain" in the language of the local people. Erta Ale is the northernmost volcano in a long chain that follows the so-called East African Rift. This rift is the not yet submerged equivalent of mid-ocean ridges—chains of undersea volcanoes that produce new seafloor. Indeed, Erta Ale spews the same kind of basaltic lava that erupts at mid-ocean ridges; past expulsions have covered the surrounding plain with so much fresh basalt that vegetation struggles to take hold (1).

LAKE OF LAVA

Atop Erta Ale is one of the earth's few quasi-permanent lava lakes. The flux of heat from the earth's interior is rarely sufficient to keep rock molten under the cooling effect of the atmosphere. Even on Erta Ale the heat sometimes slackens enough so that portions of the lake surface "freeze" into a black crust (2). Typically, though, blocks of basalt float like icebergs on the fiery liquid rock, which reaches 1,200 degrees C (2,190 degrees F) (3). Most of the Afar people do not approach the volcano, because it is thought to harbor evil spirits. Seeing an Afar warrior on the volcano's summit is unusual; this man, Ibrahim, was my guide (4). Lava emerging from cracks in the lake is particularly spectacular at night (5), when the sight evokes the phantoms of local lore.



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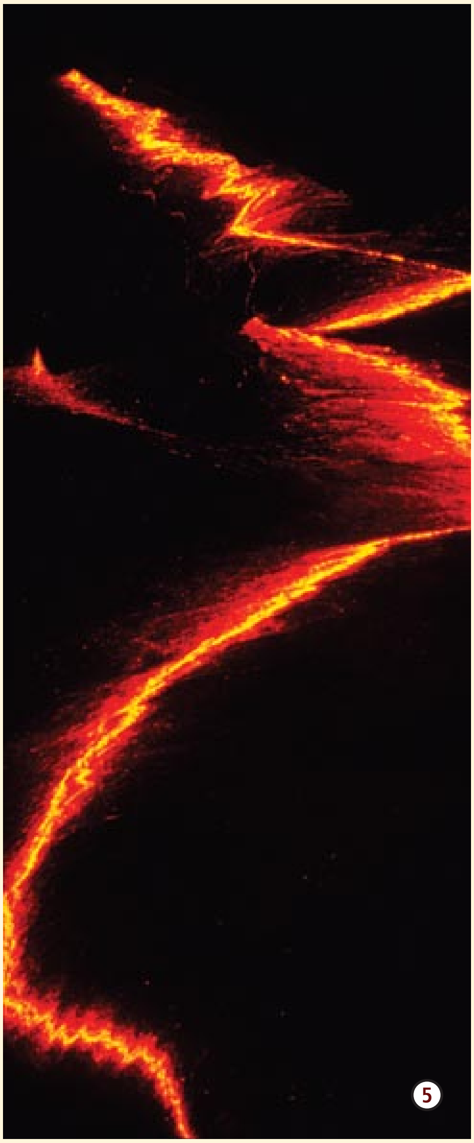

5

HELLISH HEAT

One hundred kilometers north of Erta Ale, near the Eritrea border, is the Dallol crater. There molten magma simmering below the surface fuels a vast plumbing network of superheated water. The result is a 1.6-kilometer-wide field of hydrothermal vents, geysers and hot springs (6) that call to mind the similar but more accessible environment in Yellowstone National Park in the western U.S. The mineral sulfur produces the lemon-yellow color in this earthly palette (7); blended with the signature red of oxidized iron, the sulfur stains turn orange (8). Only a few steps away from this vivid scene are drab, desiccated reminders of a hot spring's ephemeral nature (9). When an earthquake or other natural process clogs a vent's buried conduits, its minerals can lose their florid flush within a year.

LETHAL FUMES

The surreal landscape of the Dallol crater results as rainwater percolates deep underground, heats up as it contacts hot magma and rises to the surface through thick layers of salt, dissolving the salt as it travels. Recrystallization of the salt at ground level can sculpt massive structures (10) or formations as delicate as an eggshell (11). But the beauty of the sculptures can be deceiving: toxic vapors emanating from these so-called aeration mouths are yet another contributor to Afar's devilish reputation—and often require visitors to wear gas masks. More than once a surge of the ominous gas forced me to stop shooting photographs and don my mask for safety.

10

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12

POISON OR ELIXIR?

Near reddish pools of bubbling-hot, iron-rich water (12), the strong odor of hydrocarbon is a telltale sign of danger. Animals sometimes stop for a drink—not realizing it will be their last. I saw several ill-fated birds swirling in the scalding pools. But I was comforted by the irony that one organism's poison is another's elixir. The same emanations that can kill birds, insects and mammals also nourish complex communities of microbes, which thrive in many of Dallol's acidic waters. Not surprisingly, these terrestrial hot-springs communities bear striking similarities to their counterparts along submerged mid-ocean ridges.

13

14

[THE AUTHOR]

Eitan Haddok is a Paris-based photographer and reporter who specializes in earth science and the environment, with an emphasis on arid ecosystems. Haddok earned a master's degree in geophysics and planetary sciences at Tel Aviv University in 1994. For nine years before that, he worked as an environmental engineer, until deciding to unite his two passions—the earth and photography—as a way of life. Haddok's pursuit of geologic drama drew him to Iceland, where he reported on the potential likelihood that global warming is fueling volcanism there.

FATEFUL FLOODS

The salt sculptures on the opposite page and others that decorate Afar serve as a reminder that the birth of an ocean is not a singular event but rather an ongoing saga. During the 30 million years this region has been stretching thin, global sea level has fluctuated, at times filling Afar with seawater. Most recently, about 80,000 years ago, the waters of the Red Sea rose high enough to breech the low hills east of Afar, carving deep canyons (13) as they flooded the lowlands. When sea level dropped and Afar was once again cut off from the sea, the floodwaters evaporated. Wind and water sculpted the salty traces of these past inundations over the ensuing millennia, sometimes carving bizarre formations called salt mushrooms (14). In other areas, alternating layers of salt and reddish marine sediment are visible in eroded canyon walls (15).

15

AMOTZ AGNON (*Haddok*)

SALT OF THE EARTH

Salty traces of past deluges give the modern people of Afar a modest means to benefit from their baked and barren homeland. These nomadic herders collect the salt by hand, wielding wooden stakes and hatchets to break the thick layers into manageable blocks (16). The closest places to sell or exchange the salt are located in the Ethiopian highlands to the west—about a six days' walk for the camel caravans used to transport this unlikely export (17).

SCI AM For more about the birth of an ocean in Afar, go to **www.SciAm.com/oct2008**

17

MIRAGE OR HALLUCINATION?

Most years the greatest concern for the Afar people is finding adequate water. But the rains were unusually heavy in late 2006, and many of the salt fields remained flooded throughout my visit in January 2007. This unusual environmental circumstance afforded one of the most lasting impressions of my visit to Afar: as the camel caravans waded through the floodwaters, they appeared from a distance as a surreal montage of the present and future of this ocean floor in the making (18).

18

MORE TO EXPLORE

Magma-Maintained Rift Segmentation at Continental Rupture in the 2005 Afar Dyking Episode. Tim J. Wright et al. in *Nature,* Vol. 442, pages 291–294; July 20, 2006.

The Volcano–Seismic Crisis in Afar, Ethiopia, Starting September 2005. A. Ayele, E. Jacques, M.Kassim, T. Kidane, A. Omar, S. Tait, A. Nercessian, J.-B. de Chabalier and G. King in *Earth and Planetary Science Letters,* Vol. 255, Nos. 1–2, pages 177–187; March 15, 2007.

For more scientific research in the Afar region, visit the Web site of the Afar Rift Consortium at **www.see.leeds.ac.uk/afar/websitepages/aboutconsortium.htm**

Explore Eitan Haddok's photography at **www.eitanhaddok.com**

The Search *for*

KEY CONCEPTS

- Researchers have powerful new technologies to probe genes and the brain, looking for the basis of intelligence differences among individuals.
- Their work is providing a new understanding of what intelligence is, while also revealing unanticipated complexity in the interplay between genes and environment.
- The more scientists learn about the role of genes in intelligence, the more mysterious it becomes, but the quest is still worth pursuing.

—The Editors

IQ is easy to measure and reflects something real. But scientists hunting among our genes for the factors that shape intelligence are discovering they are more elusive than expected

BY CARL ZIMMER

In Robert Plomin's line of work, patience is essential. Plomin, a behavioral geneticist at the Institute of Psychiatry in London, wants to understand the nature of intelligence. As part of his research, he has been watching thousands of children grow up. Plomin asks the children questions such as "What do water and milk have in common?" and "In what direction does the sun set?" At first he and his colleagues quizzed the children in person or over the telephone. Today many of those children are in their early teens, and they take their tests on the Internet.

In one sense, the research has been a rousing success. The children who take the tests are all twins, and throughout the study identical twins have tended to get scores closer to each other than those of nonidentical twins, who in turn have closer scores than unrelated children. These results—along with similar ones from other studies—make clear to the scientists that genes have an important influence on how children score on intelligence tests.

CARY WOLINSKY

Intelligence

But Plomin wants to know more. He wants to find the specific genes that are doing the influencing. And now he has a tool for pinpointing genes that he could not have even dreamed of when he began quizzing children. Plomin and his colleagues have been scanning the genes of his subjects with a device called a microarray, a small chip that can recognize half a million distinctive snippets of DNA. The combination of this powerful tool with a huge number of children to study meant that he could detect genes that had only a tiny effect on the variation in scores.

Still, when Plomin and his co-workers unveiled the results of their microarray study—the biggest dragnet for intelligence-linked genes ever undertaken—they were underwhelming. The researchers found only six genetic markers that showed any sign of having an influence on the test scores. When they ran stringent statistical tests to see if the results were flukes, only one gene passed. It accounted for 0.4 percent of the

variation in the scores. And to cap it all off, no one knows what the gene does in the body.

"It's a real drag in some ways," Plomin says.

Plomin's experience is a typical one for scientists who study intelligence. Along with using microarrays, they are employing brain scans and other sophisticated technologies to document some of the intricate dance steps that genes and environment take together in the development of intelligence. They are beginning to see how differences in intelligence are reflected in the structure and function of the brain. Some scientists have even begun to build a new vision of intelligence as a reflection of the ways in which information flows through the brain. But for all these advances, intelligence remains a profound mystery. "It's amazing the extent to which we know very little," says Wendy Johnson, a psychologist at the University of Minnesota.

Hidden in Plain Sight

In some ways, intelligence is very simple. "It's something that everybody observes in others," says Eric Turkheimer of the University of Virginia. "Everybody knows that some people are smarter than others, whatever it means technically. It's something you sense in people when you talk to them."

Yet that kind of gut instinct does not translate easily into a scientific definition. In 1996 the American Psychological Association issued a report on intelligence, which stated only that "individuals differ from one another in their ability to understand complex ideas, to adapt effectively to the environment, to learn from experience, to engage in various forms of reasoning, to overcome obstacles by taking thought."

To measure these differences, psychologists in the early 1900s invented tests of various kinds of thought, such as math, spatial reasoning and verbal skills. To compare scores on one type of test to those on another, some psychologists developed standard scales of intelligence. The most familiar of them is the intelligence quotient, which is produced by setting the average score at 100.

IQ scores are not arbitrary numbers, however. Psychologists can use them to make strong predictions about other features of people's lives. It is possible to make reasonably good predictions, based on IQ scores in childhood, about how well people will fare in school and in the workplace. People with high IQs even tend to live longer than average.

"If you have an IQ score, does that tell you *everything* about a person's cognitive strengths and weaknesses? No," says Richard J. Haier of the University of California, Irvine. But even a simple number has the potential to say a lot about a person. "When you go see your doctor, what's the first thing that happens? Somebody takes your blood pressure and temperature. So you get two numbers. No one would say blood pressure and temperature summarize everything about your health, but they are key numbers."

Then what underlies an intelligence score? "It's certainly tapping something," says Philip Shaw, a psychiatrist at the National Institute of Mental Health (NIMH). The most influential theory of what the score reflects is more than a century old. In 1904 psychologist Charles Spearman observed that people who did well on one kind of test tended to do well on others. The link from one score to another was not very tight, but Spearman saw enough of a connection to declare that it was the result of something he called a *g* factor, short for general intelligence factor.

How general intelligence arose from the brain, Spearman could not say. In recent decades, scientists have searched for an answer by finding patterns in the test scores of large groups of people. Roughly speaking, there are two possible sources for these variations. Environmental influences—anything from the way children are raised by their parents to the diseases they may suffer as they develop—are one source. Genes

[THE AUTHOR]

Carl Zimmer is a journalist and author of seven books, including a history of brain studies, *Soul Made Flesh* (2005), and, most recently, *Microcosm:* E. coli *and the New Science of Life* (2008). He writes a column about the brain for *Discover* magazine and covers evolution, microbial life, and other topics for many newspapers and magazines. His blog, the Loom, is a winner of *Scientific American*'s Science and Technology Web awards. Zimmer wrote about evolving concepts of species and how debates over species definitions affect conservation efforts in the June issue of *Scientific American*.

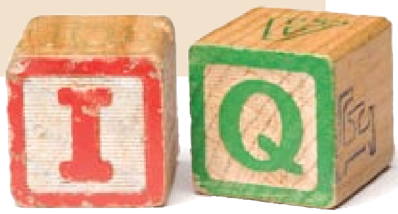
ROBERT PLOMIN studies twins to track inherited traits. His results convince him that intelligence levels are partly shaped by genes.

BEN STECHSCHULTE (*Zimmer*); NEIL HARVEY (*Plomin and twins*)

Measuring Intelligence

Alfred Binet, a French psychologist, devised the first widely used intelligence test in 1905. It was designed to predict how children would fare in school and particularly to identify those who might need extra help. Since then, tests of specific cognitive abilities, such as math, verbal and spatial reasoning skills, have been used to diagnose mental deficiencies and to define the spectrum of normal intelligence. Scores on the most common multiple-ability cognitive tests, such as the Stanford-Binet IQ test and the Wechsler Intelligence Scale, do correlate with performance in school. But the test results typically predict only about 25 percent of the variation in students' school performance, leaving 75 percent unexplained [see "How Intelligent Is Intelligence Testing?" by Robert J. Sternberg; Scientific American Presents: Exploring Intelligence, Winter 1998]. Scores on various components of the intelligence tests tend to correlate with one another, however, suggesting that the tests do gauge some general level of mental ability in a person.

Such general intelligence—also called *g*—is not assessed through a test of its own; rather it is statistically extracted from an individual's scores on other intelligence tests. Those specific ability scores have been likened to the measurements a tailor might take of arms, legs and torso, whereas *g* is more akin to the resulting suit's overall size—small, medium or large. —*The Editors*



CARY WOLINSKY

are another. Genes may shape the brain in ways that make individuals better or worse at answering questions on intelligence tests.

Starting in the 1960s, scientists have gotten clues about the roles of genes and environment by studying twins. To see why twins are so important to intelligence researchers, imagine that a pair of identical twins are separated as babies and adopted by different parents. They have the same genes but experience different environments. If their genes have no influence at all on their intelligence test scores, then you would expect that the scores would be no more similar to each other than those of two unrelated people. Yet if genes do play a critical part in intelligence, identical twins should be more similar.

"Two people with the same genes correlate as much as a person does with himself a year later," Plomin says. "Identical twins reared apart are almost as similar as identical twins reared together." But these similarities also take time to emerge. "By the age of 16 these adopted-away children resemble their biological parents' IQ just as much as kids do who are reared by their biological parents," Plomin adds.

Results such as these persuaded Plomin that genes have a crucial role in intelligence, although they clearly do not act alone. "That's what led me to say, 'What we need to do is begin to find some genes,'" he says.

Uncharted Territory

In the early 1990s, when Plomin started his search for genes, he had little company. "I knew nobody else would be crazy enough to do it," he remarks.

Plomin could not simply scan the human genome, because it had not been mapped yet. But geneticists had identified a number of genes that, if mutated in certain ways, were associated with mental retardation. Other variations in those genes, Plomin reasoned, might produce subtler differences in intelligence. He and his colleagues compared children who scored well or poorly on intelligence tests. They looked for variants of the 100 genes that showed up unusually often in one group or the other. "We didn't really find any there," he says.

So Plomin expanded the search. Rather than looking at a predefined set of genes, he mapped thousands of genetic markers sprinkled across the chromosomes of his subjects. If a marker turned up frequently in high- or low-scoring students, there might be an intelligence-linked gene not far away [*see box on next two pages*]. He and his colleagues added more children to their study so that they could detect genes with weaker effects.

At one point in the research, Plomin thought he had found an authentic link between intelligence and a gene known as *IGF2R* that encodes a growth factor receptor which is active in the brain. But when he and others tried to replicate the result, they failed. "It doesn't look like that has panned out," he says.

Plomin suspected that he needed more genetic markers to find intelligence genes. When eggs and sperm develop, their chromosomes swap segments of DNA. The closer two segments of DNA are to each other, the more likely they are to be passed down together. But in Plomin's early studies, millions of DNA nucleotides separated each pair of markers. It was possible that intelligence genes were so far from a genetic marker that they were sometimes getting passed down together and sometimes not. He needed a much denser set of genetic markers to reduce the chance of this happening.

It was with great delight that Plomin got his hands on microarrays that could detect 500,000 genetic markers—hundreds of times more than he had previously used. He and his colleagues got cheek swabs from 7,000 children, isolated their DNA, and ran it through the microarrays. And once more the results were disappointing.

"I'm not willing to say that we have found genes for intelligence," Plomin declares, "because there have been so many false positives. They're such small effects that you're going to have to replicate them in many studies to feel very confident about them."

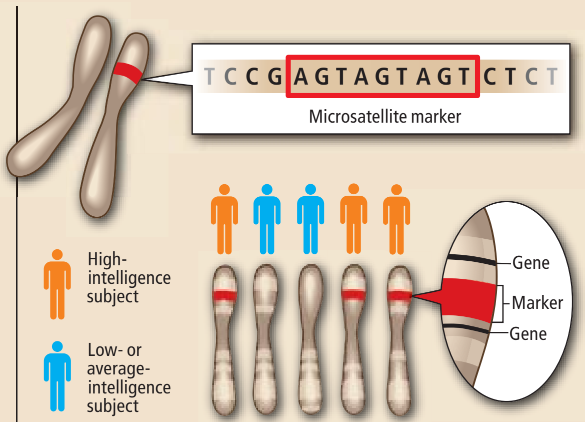
"I'm not willing to say that we have found genes for intelligence, because there have been so many false positives."

—Robert Plomin, Institute of Psychiatry, London

[TECHNIQUES]

HUNTING FOR GENES

Investigators have used various methods over the years to search for genes that might contribute to intelligence, which is a so-called quantitative trait—one present in all study subjects to greater or lesser degrees. Comparing the DNA of highly intelligent people with one another and with those of average or low intelligence can reveal patterns common to subjects of high intelligence. Those signatures, in turn, can flag the location of genes that influence intelligence levels, although such experiments have yet to conclusively identify any "intelligence genes."



QUANTITATIVE TRAIT LOCI (QTL)
To find a chromosomal region, or "locus," implicated in a quantitative trait, scientists look first for repeated DNA sequences called microsatellite markers interspersed along the length of chromosomes. If particular markers appear more frequently in high-intelligence subjects, researchers will scan nearby DNA to identify neighboring genes.

Failing to find genes for intelligence has, in itself, been very instructive for Plomin. Twin studies continue to persuade him that the genes exist. "There is ultimately DNA variation responsible for it," he says. But each of the variations detected so far only makes a tiny contribution to differences in intelligence. "I think nobody thought that the biggest effects would account for less than 1 percent," Plomin points out.

That means that there must be hundreds—perhaps thousands—of genes that together produce the full range of gene-based variation in intelligence. Plomin doubts that some genes are specialized just for verbal skills and that other genes are just for spatial understanding. In twin studies, individuals tend to have similar scores on tests for all of those different kinds of intelligence. If genes belonged to specialized sets, a person could inherit one kind of aptitude and not the others.

Plomin also surmises that his results offer some hints as to how genes influence intelligence in the brain. "If there are many genes of small effect, it's highly unlikely that they are all going to focus in one area of the brain," he argues. Instead the genes may be influencing a large network of brain regions. And each of those intelligence-associated genes may produce many different effects in different parts of the brain.

The ultimate test of Plomin's hypothesis will have to wait until scientists finally put together a list of genes that have an indisputable effect on how the brain works and that are associated with intelligence scores. That list may take a long time to come together, but Plomin is encouraged by new results from an entirely different line of research: a burst of new neuroimaging studies that attempt to find the mark of intelligence in the brain itself.

The Shape of Intelligence

Shaw and his colleagues at the NIMH have been analyzing brain scans of schoolchildren. Researchers have made images of their developing brains once a year, and Shaw has focused much of his attention on what the pictures reveal about the growth of the cortex, the outer rind of the brain where the most sophisticated information processing takes place. The cortex continues to change shape and structure until people reach their early 20s. And Shaw has found that differences in intelligence test scores are reflected in how brains develop.

In all children the cortex gets thicker as new neurons grow and produce new branches. Then the cortex thins out as branches are pruned. But in some parts of the cortex, Shaw found, development took a different course in children with different levels of intelligence. "The superclever kids started off very thin," Shaw says. "They got really relatively thicker, but in adolescence they got thinner again very quickly."

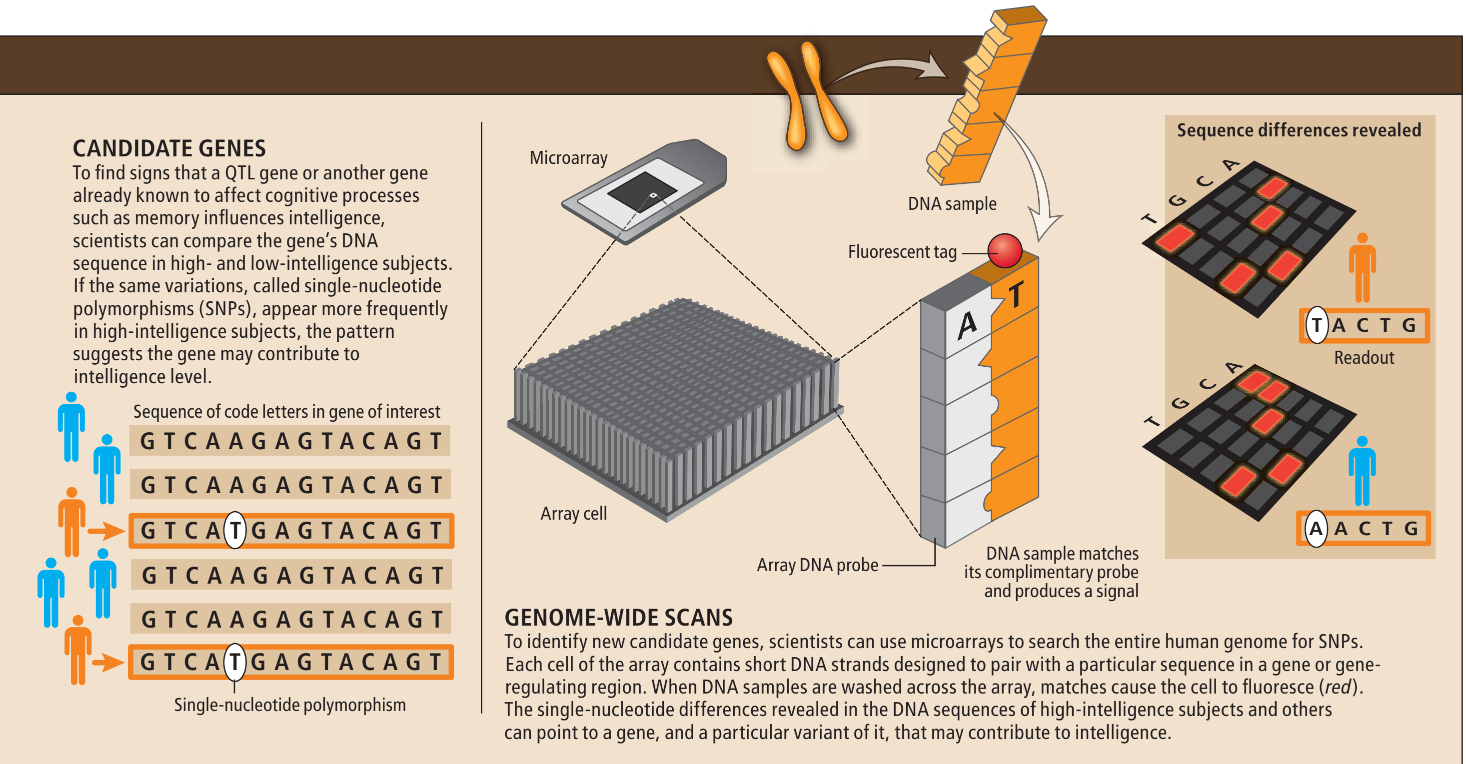
A similar pattern has emerged from studies on adult brains. Researchers have found that people with high intelligence scores tend to have certain regions of the cortex that are larger than average. Shaw expects that some of those patterns will turn out to be the result of the environment. But these regions of the cortex tend to be the same size in twins, indicating that genes are responsible for some of the difference as well.

In recent years, scientists have also published a number of studies in which they claim to have found distinctive patterns of brain functioning in people who score high on intelligence tests. Recently Haier and Rex Eugene Jung of the University of New Mexico surveyed 37 studies examining regional brain size or activity to look for an overall pattern to their results. As Plomin would have predicted, Haier and Jung found no one "intelligence spot" in the brain. Instead they identified a number of significant regions scattered around the cortex. Other studies have implicated each of these regions in different kinds of cognition. "It looks like intelligence is built on these fundamental cognitive processes,

"It looks like intelligence is built on these fundamental cognitive processes, like attention and memory, and maybe language ability."

—Richard J. Haier
University of California, Irvine

CARY WOLINSKY (*block*)



CANDIDATE GENES
To find signs that a QTL gene or another gene already known to affect cognitive processes such as memory influences intelligence, scientists can compare the gene's DNA sequence in high- and low-intelligence subjects. If the same variations, called single-nucleotide polymorphisms (SNPs), appear more frequently in high-intelligence subjects, the pattern suggests the gene may contribute to intelligence level.

GENOME-WIDE SCANS
To identify new candidate genes, scientists can use microarrays to search the entire human genome for SNPs. Each cell of the array contains short DNA strands designed to pair with a particular sequence in a gene or gene-regulating region. When DNA samples are washed across the array, matches cause the cell to fluoresce (*red*). The single-nucleotide differences revealed in the DNA sequences of high-intelligence subjects and others can point to a gene, and a particular variant of it, that may contribute to intelligence.

JEN CHRISTIANSEN (*gene illustrations*)

like attention and memory, and maybe language ability," Haier says.

Along with describing the gray matter tissue that makes up the cortex, these studies also find the signature of intelligence in the white matter that links distant parts of the cortex to one another. People with high intelligence tend to have tracts of white matter that are more organized than other people. "The white matter is like the wiring," Haier says. "If you think about it, you know, intelligence really requires processing power and speed; the white matter would give it the speed; the gray matter would give it the processing power."

Haier suggests that these parts of the "intelligence network" may work differently in different people. "You can think about being very intelligent because you have a lot of speed and a lot of processing—you have both," he says. "Or you can think about a lot of one and less of the other. All these combinations may produce the same ultimate result, so you may have two equally intelligent people, but their brains are fundamentally arriving at that behavior, however you're measuring it, in different ways."

Haier acknowledges that these ideas are little more than speculation. Still, he argues that neuroimaging has already given scientists a far more solid understanding of intelligence. "I can predict full-scale IQ with the amount of gray matter in a small number of areas," he says. Haier suspects that in the near future, 10 minutes in a magnetic resonance imaging scanner may reveal as much about high school students as four hours taking an SAT exam.

Some psychologists are not quite ready to take that step. They do not think IQ and *g* should be endowed with a deeper significance than they deserve. For one thing, there is much beyond the life of the mind than mentally rotating cubes and completing analogies. "I think human intelligence is multifaceted and very complex," the University of Virginia's Turkheimer says. Unfortunately, he adds, barely any work has been done on other facets of intelligence.

"We can use g for a lot of useful things, but I don't believe it follows from that that human intelligence is a unitary thing called *g* that we can find in a literal way in the brain," he says. Longitude and latitude are useful, too, for navigation, he notes, but that does not mean there is actually a grid carved into the earth.

Johnson of the University of Minnesota defends the *g* factor as tapping into something important in the brain, but, like Haier, she does not think it is a one-size-fits-all general intelligence. "While there is something general about intelligence, what makes my intelligence general is not the same thing that makes your intelligence general or any other person's," she says. "Our brains are plastic enough that we put together, each of us, a different kind of general intelligence."

Pinpointing the role genes have in producing

GLOSSARY

Genome-wide association study (GWAS): An approach that involves rapidly scanning tens or hundreds of thousands of markers across the complete genomes of thousands of people to find variations associated with a particular trait.

Statistical power: The larger the pool of subjects in a GWAS, the greater the chances of detecting variations that have small but significant effects on the trait.

Effect size: Statistical analysis determines what percentage of the differences among individuals in the trait are attributable to a specific DNA variant.

> **"Our brains are plastic enough that we put together, each of us, a different kind of general intelligence."**
>
> *—Wendy Johnson, University of Minnesota*

different kinds of intelligence will no doubt be very difficult. And it is entirely possible that a list of intelligence-linked genes may include many that do not actually have brain-specific functions. Turkheimer offers the following thought experiment: Imagine a gene that is related to the width of a woman's birth canal. Women who carry a gene for a narrow birth canal tend to have more trouble in labor, and their babies run a higher risk of being oxygen-deprived. As a result, their babies, on average, have IQ scores a couple points below those who have a different version of the gene. And some of those children will also carry the narrow-canal gene.

"These babies are going to have a gene that's correlated with low IQ," Turkheimer says. "So do you conclude that that's an IQ gene? Well, not really; it's a birth-canal gene. The ways that genes could correlate with IQ are so variable that it's almost impossible to know."

Turkheimer's own research illustrates another kind of complexity in the link from genes to intelligence: genes do not act in isolation from the environment. In fact, the same gene can have different effects in different environments. Turkheimer was led to this realization when he noticed that the large twin studies on intelligence contained few poor children. "Very poor people don't have the time or the resources or the interest to do volunteer studies," he says.

Other databases, Turkheimer discovered, have more poor children in their ranks. He was able to analyze the test scores of hundreds of twins, taking into consideration their socioeconomic status—a category based on factors that include a family's income and the education level of the parents. He found that the strength of genes' effect depended on the socioeconomic status of the children. In children from affluent families, about 60 percent of the variance in IQ scores could be accounted for by genes. For children from impoverished families, on the other hand, genes accounted for almost none.

Turkheimer and his colleagues published these results in 2003; in May 2007 they replicated the pattern with another database. Instead of comparing IQ scores, the researchers looked at how 839 pairs of twins fared on the National Merit Scholarship Qualifying Test in 1962. Once more genes played little role in the variance of scores among poor children and played a far stronger one in more affluent children. Turkheimer posits that poverty brings with it powerful environmental forces that may shape intelligence from the womb through school and onward. But when children grow up in the relative stability of an affluent home, gene-based differences can begin to make themselves felt.

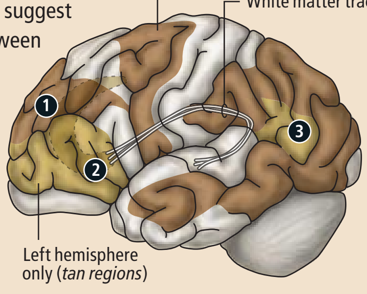
As if this complexity was not enough, scientists are also finding that genes, in turn, can alter the effect that the environment has on our intelligence. Last year British scientists found an association between breast-feeding and a boost in IQ test scores—but only if children carried a particular variant of a particular gene. If they carried another variant, breast-fed children scored no differently than children who drank formula.

Genes may also influence behavior in ways that influence how intelligence develops. "People create their own environments," Johnson says. "If you see a kid who's really interested in art or math, you're just more likely to go out and get him a math book or some crayons. So they'll practice it and become more different from the kid who doesn't have the math book. Parents

[TECHNIQUES]

SCANNING THE BRAIN

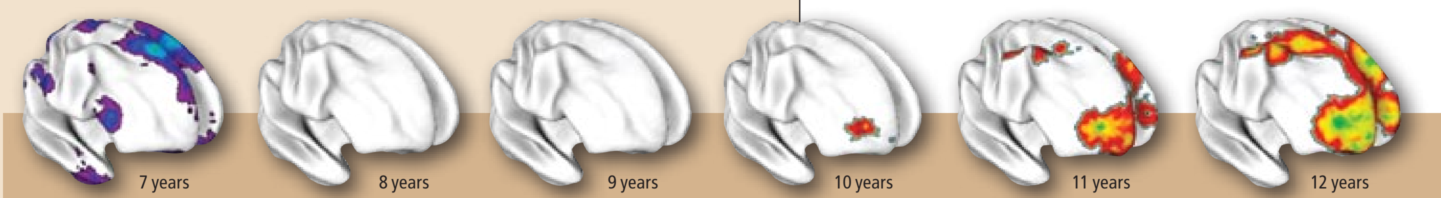
Imaging technologies have identified differences between high-intelligence subjects and others in the size and activity levels of certain brain regions. Such studies also suggest that the efficiency of information exchange between these areas is a critical factor in intelligence.



BRAIN REGIONS linked to intelligence levels through scans are responsible for diverse processes such as reasoning (*1*), language (*2*) and sensory integration (*3*). Moreover, white matter tracts linking brain regions are more organized in high-intelligence subjects, suggesting that information transmission also plays an important role.

SIZE OF CORTEX

BRAIN DEVELOPMENT over time displays patterns linked to intelligence. In high-IQ children, areas of the cerebral cortex are thinner than average in early years, then become thicker than normal in adolescence. How these differences affect information processing remains unknown.



JEN CHRISTIANSEN; SOURCE: REX EUGENE JUNG *University of New Mexico* AND RICHARD J. HAIER *University of California, Irvine*

BACK TO BASICS

The largest human genome scan to date tested 7,000 subjects for 500,000 SNPs but turned up only six that seem implicated in intelligence, each with a tiny effect on the differences among people. Three of the SNPs were in DNA regions between genes; the others were in parts of genes that do not encode proteins. All could have regulatory effects on gene activity, but the functions of the proteins encoded by the three known genes suggest that the SNPs may not influence cognition in obvious ways; rather they could lead to subtle variations in basic brain development and cell perfomance.

SNP	GENOME LOCATION	ROLE OF SURROUNDING DNA	EFFECT SIZE
1	Between genes	Unknown	0.2%
2	Between genes	Unknown	0.2%
3	Between genes	Unknown	0.1%
4	In gene *DNAJC13*	Encodes a "chaperone" protein that supports many cell functions	0.4%
5	In gene *TBC1D7*	Encodes a protein that activates an enzyme involved in protein manufacture, basic cell maintenance and sensory processing	0.1%
6	In gene *FADS3*	Encodes a protein involved in synthesizing fatty acids and controlling their levels in cell membranes	0.2%

respond to what the kid does. Our models don't measure that well at all."

This effect might explain one of the most puzzling patterns in twin studies on intelligence: how the influence of genes becomes stronger on test scores as people get older. Genes may affect how people mold their intellectual environment. Choosing to seek out new experiences, reading books and engaging in conversations may alter the brain. And as children grow up and take over control of their own lives, this effect may get stronger.

"Intelligence is kind of an emergent property of the brain," Shaw says. "The idea that you're born with 15 genes, and they set in stone how intelligent you're going to be and how your brain is going to develop, is almost certainly wrong."

Why Study Intelligence?

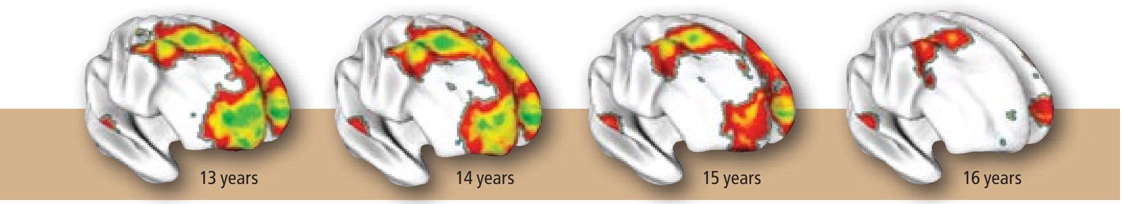
Intelligence may be enormously complex, and scientists may have made frustratingly little progress in understanding it. Yet many experts on intelligence still see some practical values in continuing the quest. Haier, for example, hopes that a brain-based understanding of intelligence will help teachers design strategies for educating children most effectively.

"It's very important as we enter the 21st century to maximize and optimize education for people," he argues. "That's what's at stake."

By understanding people's genetic profiles, Plomin suggests, it may be possible to find the best ways to foster learning. If, as he anticipates, microarray studies finally do reveal intelligence genes, it may then be possible to test children for which versions they carry.

"You could get an index of genetic risk," Plomin says. "You could see which kids are at genetic risk for reading disability, and you could then intervene. The hope is that you could predict and intervene with programs to prevent those problems rather than waiting until they occur in school."

And for some psychologists, it is enough that intelligence is such an intriguing part of human nature. "Intelligence and intelligence test scores are in many ways the best predictor in all of psychology," Turkheimer says. "That's what makes it fascinating. If you know my SAT scores and you want to know how I'm going to perform at practically anything, those SAT scores are far from a perfect predictor, but they're far better than knowing about my personality. Intelligence really works. There's this palpable psychological quality that allows you to make predictions about humans but gets very slippery when you try to tie it down in concrete numerical ways. So it's just a very interesting scientific problem." ■



PHILIP SHAW *Child Psychiatry Branch, National Institute of Mental Health (brain scans)*

➥ MORE TO EXPLORE

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Web Science EMERGES

Studying the Web will reveal better ways to exploit information, prevent identity theft, revolutionize industry and manage our ever growing online lives

By Nigel Shadbolt and Tim Berners-Lee

KEY CONCEPTS

- The relentless rise in Web pages and links is creating emergent properties, from social networking to virtual identity theft, that are transforming society.
- A new discipline, Web science, aims to discover how Web traits arise and how they can be harnessed or held in check to benefit society.
- Important advances are beginning to be made; more work can solve major issues such as securing privacy and conveying trust.

—The Editors

Since the World Wide Web blossomed in the mid-1990s, it has exploded to more than 15 billion pages that touch almost all aspects of modern life. Today more and more people's jobs depend on the Web. Media, banking and health care are being revolutionized by it. And governments are even considering how to run their countries with it. Little appreciated, however, is the fact that the Web is more than the sum of its pages. Vast emergent properties have arisen that are transforming society. E-mail led to instant messaging, which has led to social networks such as Facebook. The transfer of documents led to file-sharing sites such as Napster, which have led to user-generated portals such as YouTube. And tagging content with labels is creating online communities that share everything from concert news to parenting tips.

But few investigators are studying how such emergent properties have actually happened, how we might harness them, what new phenomena may be coming or what any of this might mean for humankind. A new branch of science—Web science—aims to address such issues. The timing fits history: computers were built first, and computer science followed, which subsequently improved computing significantly. Web science was launched as a formal discipline in November 2006, when the two of us and our colleagues at the Massachusetts Institute of Technology and the University of Southampton in England announced the beginning of a Web Science Research Initiative. Leading researchers from 16 of the world's top universities have since expanded on that effort.

This new discipline will model the Web's structure, articulate the architectural principles that have fueled its phenomenal growth, and discover how online human interactions are driven by and can change social conventions. It will elucidate the principles that can ensure that the network continues to grow productively and settle complex issues such as privacy protection and intellectual-property rights. To achieve these ends, Web science will draw on mathematics, physics, computer science, psychology, ecology, sociology, law, political science, economics, and more.

Of course, we cannot predict what this nascent endeavor might reveal. Yet Web science has already generated crucial insights, some presented here. Ultimately, the pursuit aims to answer fundamental questions: What evolutionary patterns have driven the Web's growth? Could they burn out? How do tipping points arise, and can that be altered?

Insights Already

Although Web science as a discipline is new, earlier research has revealed the potential value of such work. As the 1990s progressed, searching for information by looking for key words among the mounting number of pages was returning more and more irrelevant content. The founders of Google, Larry Page and Sergey Brin, realized they needed to prioritize the results.

Their big insight was that the importance of a page—how relevant it is—was best understood in terms of the number and importance of the pages linking to it. The difficulty was that part of this definition is recursive: the importance of a page is determined by the importance of the

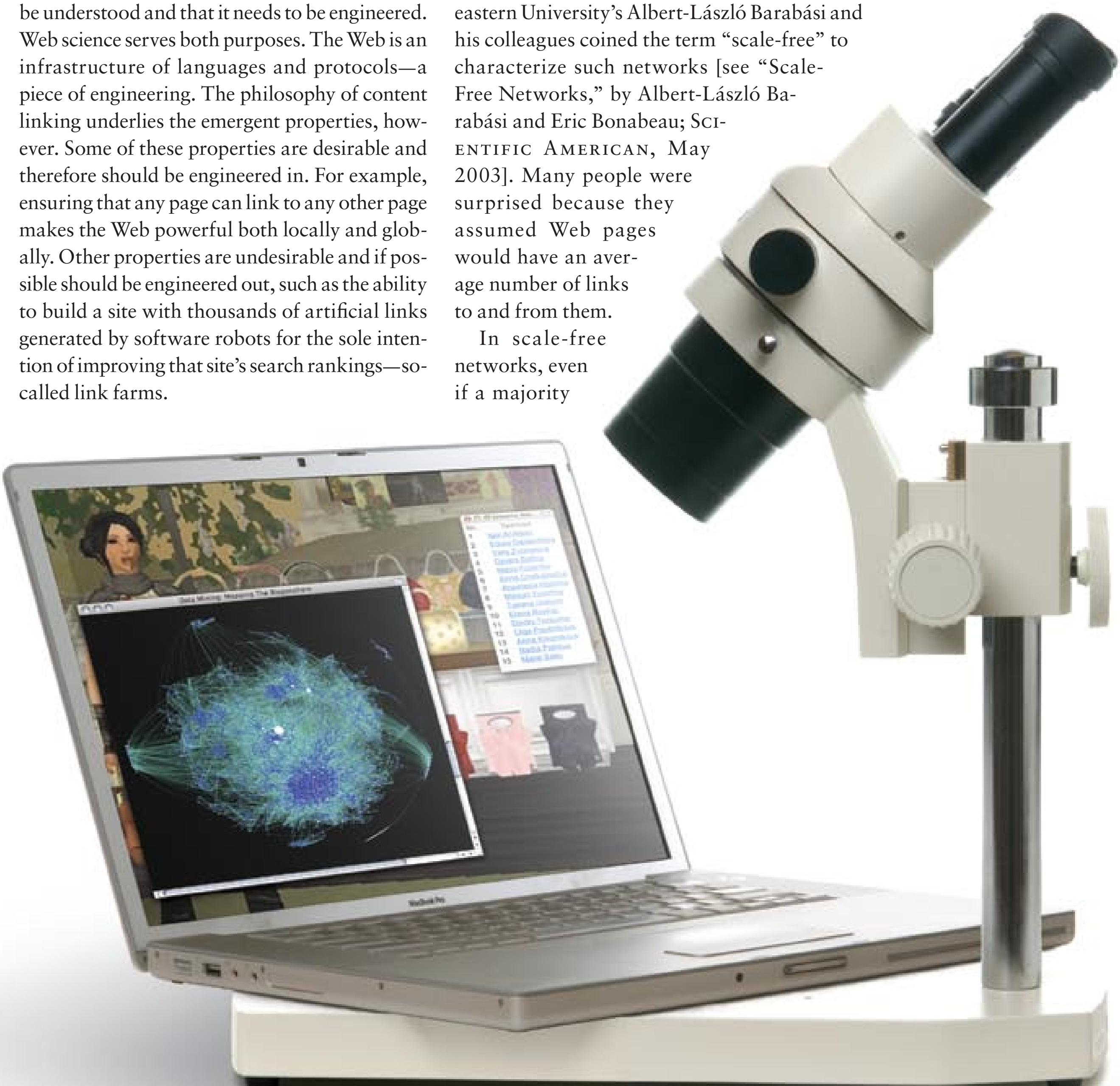
CARY WOLINSKY; MATTHEW HURST *Microsoft Live Labs* (http://datamining.typepad.com/data_mining) (blogosphere visualization)

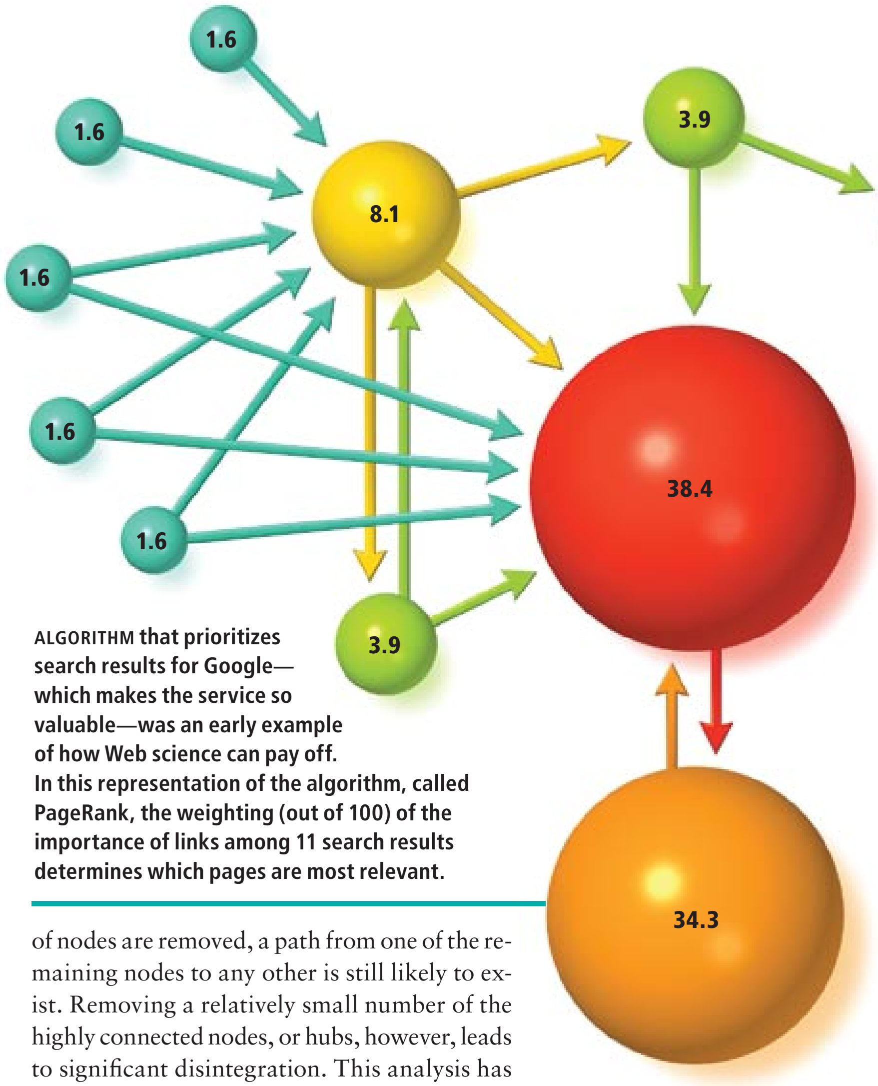
pages linking to it, whose importance is determined by the importance of the pages linking to them. Page and Brin figured out an elegant mathematical way to represent that property and developed an algorithm they called PageRank to exploit the recursiveness, thus returning pages ranked from most relevant to least.

Google's success shows that the Web needs to be understood and that it needs to be engineered. Web science serves both purposes. The Web is an infrastructure of languages and protocols—a piece of engineering. The philosophy of content linking underlies the emergent properties, however. Some of these properties are desirable and therefore should be engineered in. For example, ensuring that any page can link to any other page makes the Web powerful both locally and globally. Other properties are undesirable and if possible should be engineered out, such as the ability to build a site with thousands of artificial links generated by software robots for the sole intention of improving that site's search rankings—so-called link farms.

Another early discovery, which came from graph theory, is that the Web's connectivity follows a so-called power-law degree distribution. In many networks, nodes have about the same number of links to them. But on the Web a few pages have a huge number of other pages linking to them, and a very large number of pages have only a few pages linking to them. Northeastern University's Albert-László Barabási and his colleagues coined the term "scale-free" to characterize such networks [see "Scale-Free Networks," by Albert-László Barabási and Eric Bonabeau; Scientific American, May 2003]. Many people were surprised because they assumed Web pages would have an average number of links to and from them.

In scale-free networks, even if a majority





ALGORITHM **that prioritizes search results for Google—which makes the service so valuable—was an early example of how Web science can pay off. In this representation of the algorithm, called PageRank, the weighting (out of 100) of the importance of links among 11 search results determines which pages are most relevant.**

of nodes are removed, a path from one of the remaining nodes to any other is still likely to exist. Removing a relatively small number of the highly connected nodes, or hubs, however, leads to significant disintegration. This analysis has been crucial for the companies and organizations—be they telecommunications providers or research laboratories—that design how information is routed on the Web, allowing them to build in substantial redundancy that balances traffic and makes the network more resistant to attack.

Thorough understanding of scale-free networks, gleaned by analyzing the Web, has prompted experts to analyze other network systems. They have since found power-law degree distributions in areas as far-flung as scientific citations and business alliances. The work has helped the U.S. Centers for Disease Control and Prevention improve its models of sexual disease transmission and has helped biologists better understand protein interactions.

Scientific analysis has also characterized the Web as having short paths and small worlds. While at Cornell University in the 1990s, Duncan J. Watts and Steven H. Strogatz showed that even though the Web was huge, a user could get from one page to any other page in at most 14 clicks. Yet to fully understand these traits, we need to appreciate that the Web is a social network. In 1967 Harvard University psychologist Stanley Milgram asked residents in Omaha, Neb., and Wichita, Kan., to attempt to send a package to an individual described only by his name, some general features and the fact that he lived in Boston. The residents were to send the package to an intermediary who they thought might know more about how to reach the individual and who could then send it on to another intermediary. Eventually 64 of the almost 300 packages made it to the designated recipients. On average the number of intermediaries needed was six—the basis of the catchphrase "six degrees of separation."

More recently, however, Watts, now at Columbia University, tried to repeat the experiment with an e-mail message to be forwarded on the Web and experienced failures in path finding. In particular, if individuals had no incentive to forward the note the paths broke down. Yet only very slight incentives improved matters.

The lesson is that network structure alone is not everything; networks thrive only in the light of the actions, strategies and perceptions of the individuals embedded in them. To realistically know why the Web has a beneficial structure of short paths, we need to know why people who contribute content link it to other material. Social drivers—goals, desires, interests and attitudes—are fundamental aspects of how links are made. Understanding the Web requires insights from sociology and psychology every bit as much as from mathematics and computer science.

SEXUAL ORIENTATION REVEALED

Carter Jernigan and Behram Mistree, both students at the Massachusetts Institute of Technology, recently analyzed Facebook communities. They found that the structure identifies the likely sexual orientation of individuals who have not explicitly stated their preference. The reason is that people who have made a declaration link more often to others of a similar orientation; a kind of triangulation emerges. This sort of result raises ethical and privacy questions; more research about the Web's structure and users' behavior could provide answers.

From Micro to Macro

One major area of Web science will explore how a small technical innovation can launch a large social phenomenon. A striking example is the emergence of the blogosphere. Although early Web browsers did not provide a handy way for the average person to "publish" his or her ideas, by 1999 blog programs had made self-publishing much easier. Blogging subsequently caught fire because as people got issues off their chest, they also found others with similar views who could readily assemble into a like-minded community.

It is difficult to estimate the size of the blogosphere accurately. David Sifry's leading blog search engine, called Technorati, was tracking more than 112 million blogs worldwide in May of this year, a number that may include only a mere fraction of the 72 million blogs purportedly in China. Whatever the size, the explosive

GEORGE RETSECK

growth demands an explanation. Arguably, the introduction of very simple mechanisms, especially TrackBack, facilitated the growth. If a blogger writes an entry commenting on or referring to an entry at another blog, TrackBack notifies the original blog with a "ping." This notification enables the original blog to display summaries of all the comments and links to them. In this way, conversations arise spanning several blogs and rapidly form networks of individuals interested in particular themes. And here again large portions of the blog structure become linked via short paths—not only the blogs and bloggers themselves but also the topics and entries made.

As blogging blossomed, researchers quickly created interesting tools, measurement techniques and data sets to try to track the dissemination of a topic through blogspace. Social-media analyst Matthew Hurst of Microsoft Live Labs collected link data for six weeks and produced a plot of the most active and interconnected parts of the blogosphere [*see illustration on next page*]. It showed that a number of blogs are massively popular, seen by 500,000 different individuals a day. A link or mention of another blog by one of these superblogs guarantees a lot of traffic to the site referenced. The plot also shows isolated groups of dedicated enthusiasts who are very much in touch with one another but barely connect to other bloggers.

If exploited correctly, the blogosphere can be a powerful medium for spreading an idea or gauging the impact of a political initiative or the likely success of a product launch. The much anticipated release of the Apple iPhone generated 1.4 percent of all new postings on its launch day. One challenge is to understand how this dissemination might change our view of journalism and commentary. What mechanisms can assure blog readers that the facts quoted are trustworthy? Web science can provide ways to check this so-called provenance of information, while offering practical rules about conditions surrounding its reuse. Daniel Weitzner's Transparent Accountable Datamining Initiative at M.I.T. is doing just that.

Rise of Semantics

One emerging phenomenon that is benefiting from concerted research is the rise of the Semantic Web—a network of data on the Web. Among many payoffs, the Semantic Web promises to give much more targeted answers to our questions. Today searching Google for "Toyota used cars for sale in western Massachusetts under $8,000" returns more than 2,000 general Web pages. Once Semantic Web capabilities are added, a person will instead receive detailed information on seven or eight specific cars, including their price, color, mileage, condition and owner, and how to buy them.

Engineers have devised powerful foundations for the Semantic Web, notably the primary language—the Resource Description Framework (RDF)—which is layered on top of the basic HTML and other protocols that form Web pages. RDF gives meaning to data through sets of "triples." Each triple resembles the subject, verb and object of a sentence. For example, a triple can assert that "person X" [subject] "is a sister of" [verb] "person Y" [object]. A series of triples can determine that [car X] [is brand] [Toyota]; that [car X] [condition is] [used]; that [car X] [costs] [$7,500]; that [car X] [is located in] [Lenox]; and that [Lenox] [is located in] [western Massachusetts]. Together these triples can conclude that car X is indeed a proper answer to our query. This simple triple structure turns out to be a natural way to describe a large majority of the data processed by machines. The subjects, verbs and objects are each identified by a Universal Resource Identifier (URI)—an address just like that used for Web pages. Thus, anyone can define a new concept, or a new verb, by defining a URI for it on the Web.

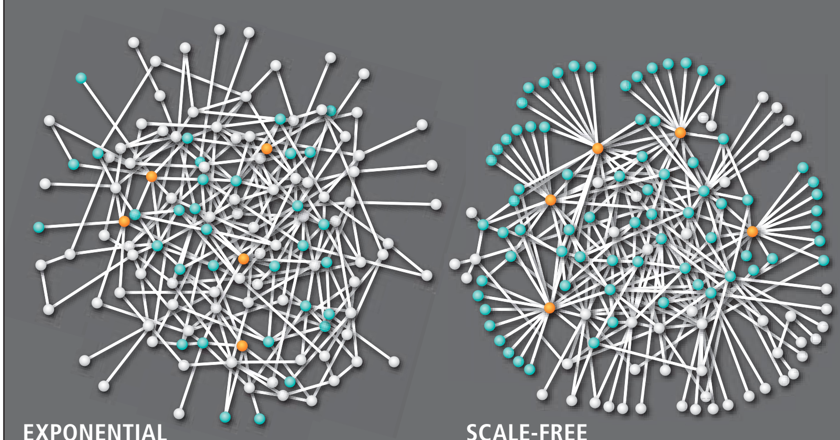
[THE AUTHORS]

Nigel Shadbolt (*left*) is professor of artificial intelligence at the University of Southampton in England, chief technology officer of the Semantic Web company Garlik Ltd., and a past president of the British Computer Society. **Tim Berners-Lee** (*right*) invented the World Wide Web and leads the World Wide Web Consortium, based at the Massachusetts Institute of Technology.

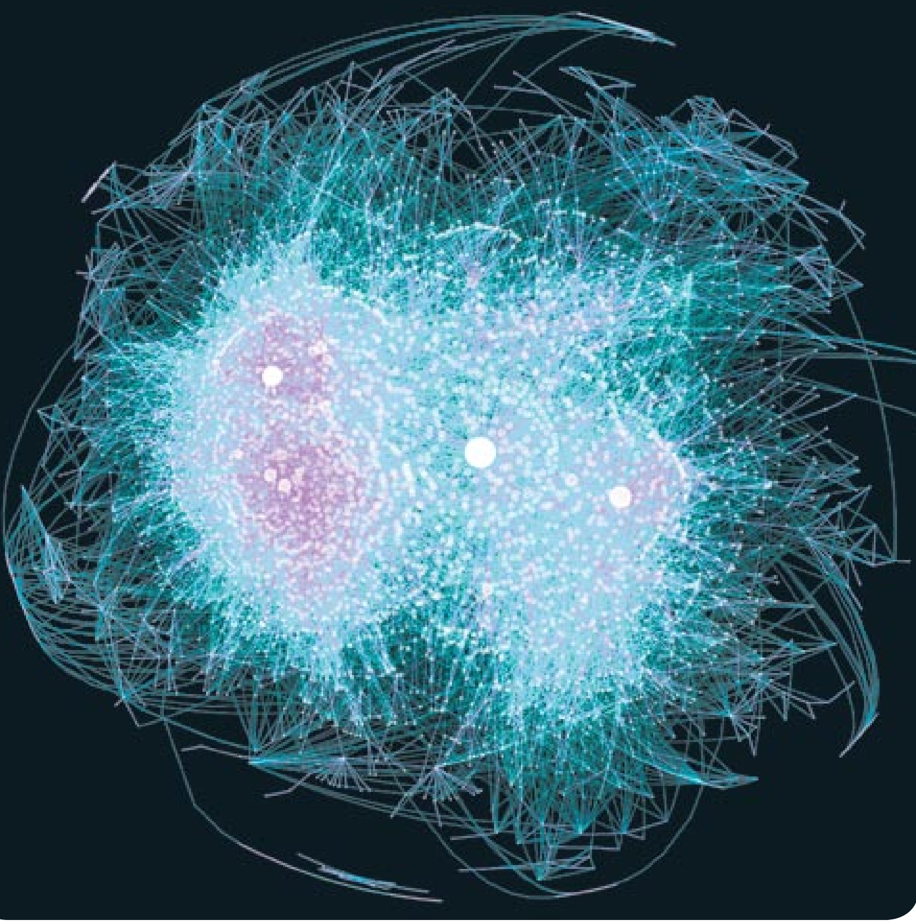
[WORK IN PROGRESS]

Building a More Secure Web

Understanding how the Web is linked can reveal ways to better engineer it. Many networks are fairly homogeneous (an "exponential" structure): nodes, even the busiest (*orange*) and their immediate neighbors (*blue*), have roughly the same number of links to and from them. But analysis at the University of Notre Dame showed that the Web is a scale-free network: a few nodes (Web sites) have many links coming in, and many nodes have only a few links.



JASON BUCKNER (*Shadbolt*); DONNA COVENEY (*Berners-Lee*); SOURCE: "ERROR AND ATTACK TOLERANCE OF COMPLEX NETWORKS," BY RÉKA ALBERT, HAWOONG JEONG, ALBERT-LÁSZLÓ BARABÁSI ET AL., IN *NATURE*, VOL. 406; JULY 27, 2000 (*scale-free network*)



BLOGOSPHERE has certain patterns of power. Matthew Hurst tracked how blogs link to one another. A visualization of the result (*left*) displays each blog as a white dot; the few large dots are massively popular sites. Blogs that share numerous cross citations form distinct communities (*purple*). Isolated groups that communicate frequently among themselves but rarely with others appear as straight lines along the outer edges.

MATTHEW HURST *Microsoft Live Labs (http://datamining.typepad.com/data_mining) (blogosphere visualization)*

As these definitions grow and interlink, specialists and enthusiasts will define taxonomies and ontologies: data sets that describe classes of objects and relations among them. These sets will help computers everywhere to find, understand and present targeted information.

Numerous groups are already building Semantic Web frameworks, especially in biology and health care [see "The Semantic Web in Action," by Lee Feigenbaum; SCIENTIFIC AMERICAN, December 2007]. More than 1,000 people attended the Semantic Technology conference in San Jose, Calif., this past May. Web science offers the prospect of creating more powerful ways to define, link and interpret data.

The wiki world offers a good example of how useful such exploitation of linked data can be. As of May, Wikipedia, the online encyclopedia generated by people everywhere, had more than 2.3 million articles in English. The articles contain regular text, along with infobox templates—sets of facts. More than 700,000 English infobox templates now exist, and programmers are looking for ways to mine them. One effort is the DBpedia project, begun by Chris Bizer and his colleagues at the Free University of Berlin and the University of Leipzig in Germany. They have devised a tool by the same name (available at http://wikipedia.aksw.org) that uses Semantic Web techniques to query the infoboxes. It can ask for all tennis players who live in Moscow or the names of all the mayors of towns in the U.S. that are at an altitude greater than 1,000 meters [*see box below*] and get back an exact answer.

Naturally, we would like a similar tool for the entire Web, but developing one would require that more and more data on the Web were represented as linked sets of RDF. Meanwhile it is becoming apparent that DBpedia's link structure obeys the same power laws that have been found for the Web. Just as some pages have a higher rank in the Web of documents, so it will be for data on the Semantic Web. At the same time, research by Oded Nov of the Polytechnic Institute of New York University is beginning to ascertain why Wikipedians post entries and what motivates their activity; the psychological drivers that are revealed will help us understand how to encourage people to contribute to the Semantic Web.

Future Challenges

It seems sensible to say that Web science can help us engineer a better Web. Of course, we do not fully know what Web science is, so part of the new discipline should be to find the most powerful concepts that will help the science

[CASE STUDY]

Tennis, Anyone?

Web science is generating tools that can understand online data (known as the Semantic Web) and can therefore provide highly targeted search results. One effort, DBpedia, can assess the information in infoboxes on Wikipedia pages. For example, to find all tennis players from Moscow, a user fills in a simple form (*below*) and gets a short, exact list as a result (*right*).

Subject	Predicate	Object
person	placebirth	Moscow
person	type	tennis_players

Semantic Wiki...

Nr.	?person
1	Igor Andreev
2	Elena Dementieva
3	Vera Zvonareva
4	Dinara Safina
5	Maria Kirilenko
6	Anna Chakvetadze
7	Anastasia Myskina
8	Mikhail Youzhny
9	Tatiana Golovin
10	Elena Bovina
11	Dmitry Tursunov
12	Olga Poutchkova
13	Anna Kournikova
14	Nadia Petrova
15	Marat Safin

LINDEN LAB

SECOND LIFE **and other virtual worlds are constructed by many enthusiasts who each contribute small pieces, such as stores and products that constitute a virtual mall where real people can profit from online avatars that shop there. Such creations raise complicated questions about who owns what intellectual property—questions Web science hopes to answer.**

itself grow. Perhaps insights will come from the work's interdisciplinary nature. For example, biological concepts such as plasticity might prove useful. The brain and nervous system grow and adapt over our lifetimes by forming and deleting connections between neurons—the brain cells that act as nodes in our neural network. Changes in the connections occur in response to activity in the network, including learning, disuse and aging.

Similarly, Web connections decay and grow. Web science could also explore the possibility of protocols that disconnect Web nodes if there is no inbound or outbound activity. Would such a network function more effectively?

Concepts such as population dynamics, food chains, and consumers and producers all have counterparts on the Web. Perhaps methods and models devised for ecology can help us understand the Web's digital ecosystem, which could be prone to damage by single major events (analogous to hurricanes) or subtle but steady erosions (like invasive species).

We will also need to examine a range of legal issues. Laws relating to intellectual property and copyright for digital material are already being debated. Fascinating issues have arisen in virtual environments such as Second Life; for example, do laws and entitlements transfer to digital worlds, where millions of people contribute tiny additions to existing content? Another issue is whether we can build rules of use into content itself. An example of such a framework, called Creative Commons, lets authors, scientists, artists and educators easily mark their creative work with the freedoms and restrictions they want it to carry. Crucially, the mark also provides RDF data that describe the license, making it easy to automatically locate works and understand their conditions of use. Web science could determine whether commons-style licenses affect the spread of the information.

Sociology is another field to tap. Research is needed, for instance, to provide Web users with better ways of determining whether material on a site can be trusted. How can we determine whether we can trust the material emanating from a site? The Web was originally conceived as a tool for researchers who trusted one another implicitly; strong models of security were not built in. We have been living with the consequences ever since.

As a result, substantial research should be devoted to engineering layers of trust and provenance into Web interactions. The coming together of our digital and physical personas presents opportunities for progress, such as the integration of financial, medical, social and educational services for each of us. But it is also an opportunity for identity theft, cyberstalking and cyberbullying, and digital espionage. Web science can help enhance the good and ameliorate the bad.

Various other questions need to be tackled before the rich potential of the Web can be mined to its fullest. How do social norms influence emerging capabilities? How can online privacy protection, intellectual-property rights and security be implemented? What trends could fragment the Web?

Many people are working on parts of these questions. Web science can bring their efforts together and compound the insights. We need to train a cadre of researchers, developers, practitioners and users in a broad range of skills and subjects. They will help us fully understand the Web and discover how to engineer it for the 21st century and beyond. ■

➥ MORE TO EXPLORE

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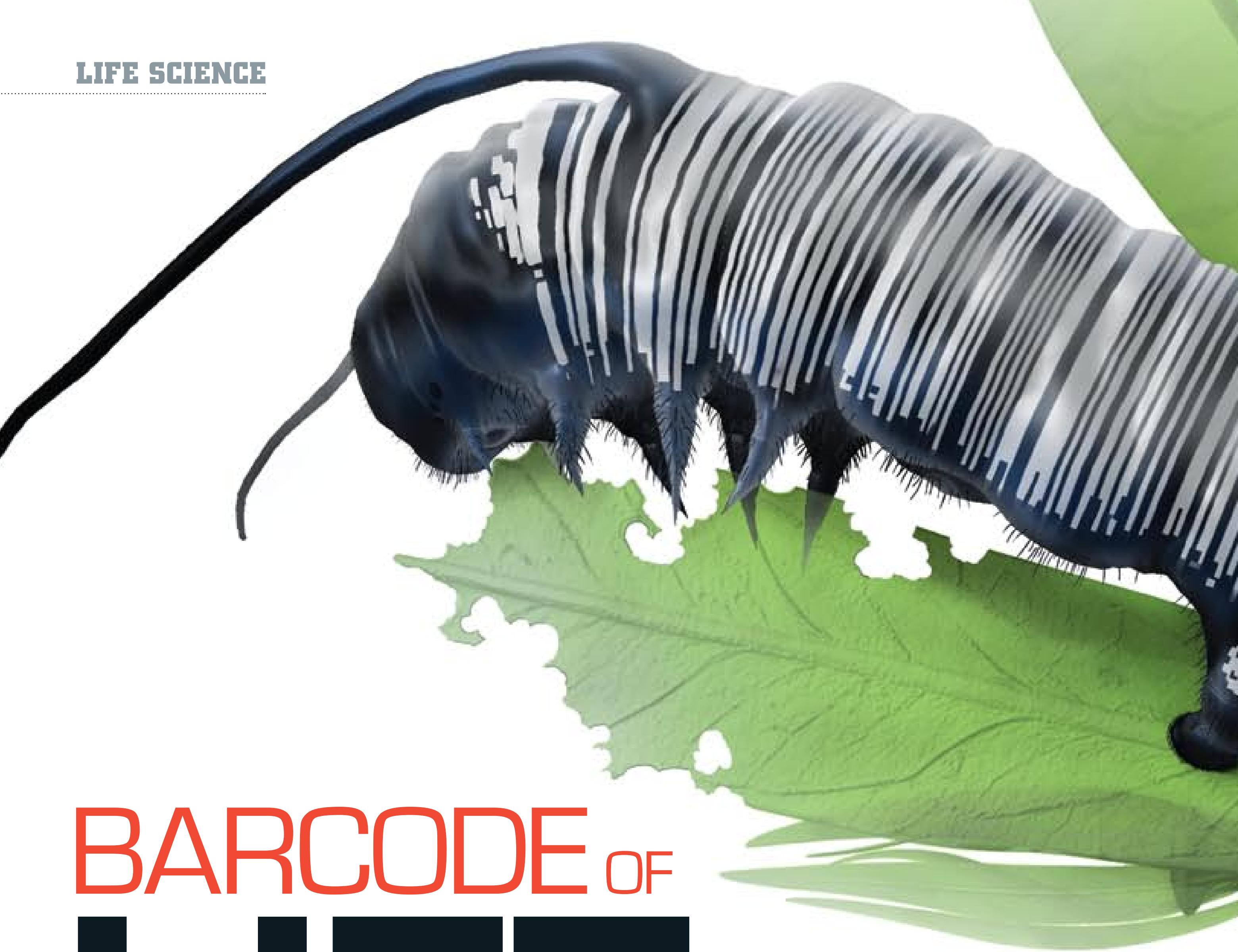


BARCODE OF LIFE

Inspired by commercial barcodes, DNA tags could provide a quick, inexpensive way to identify species

BY MARK Y. STOECKLE AND PAUL D. N. HEBERT

Wandering the aisles of a supermarket several years ago, one of us (Hebert) marveled at how the store could keep track of the array of merchandise simply by examining the varying order of thick and thin lines that make up a product's barcode. Why, he mused, couldn't the unique ordering of the four nucleic acids in a short strand of DNA be mined in a similar way to identify the legions of species on earth?

Ever since Carl Linnaeus began systematically classifying all living things 250 years ago, biologists have looked at various features—color, shape, even behavior—to identify animals and plants. In the past few decades, researchers have begun to apply the genetic information in DNA

AMADEO BACHAR

to the task. But both classical and modern genetic methods demand great expertise and eat up huge amounts of time. Using just a small section of the DNA—something more akin to the 12-digit barcode on products—would require far less time and skill.

So we set a challenge for ourselves: to find a segment of DNA—the same part of the same gene for every species—that would reliably distinguish one animal species from another. Looking ahead, we expect that soon a handheld barcode reader, similar to a GPS device, will "read" such a segment from any tiny piece of tissue. An inspector at a busy seaport, a hiker on a mountain trail, or a scientist in a lab could insert a sample containing DNA—a snippet of whisker, say, or the leg of an insect—into the device, which would detect the sequence of nucleic acids in the barcode segment. This information would be relayed instantly to a reference database, a public library of DNA barcodes, which would respond with the specimen's name, photograph and description. Anyone, anywhere, could identify species and could also learn whether some living thing belongs to a species no one has ever recognized before.

Why We Need Barcoding

Morphology—the shape and structure of plants and animals—has enabled scientists to designate some 1.7 million species, a remarkable feat, and morphology remains the foundation of Linnaean-type taxonomic diagnosis. Relying on morphology alone to describe life's diversity has limits, however. The nuances that distinguish closely allied species are so complex that most taxonomists specialize in one group of closely related organisms. As a result, a multitude of

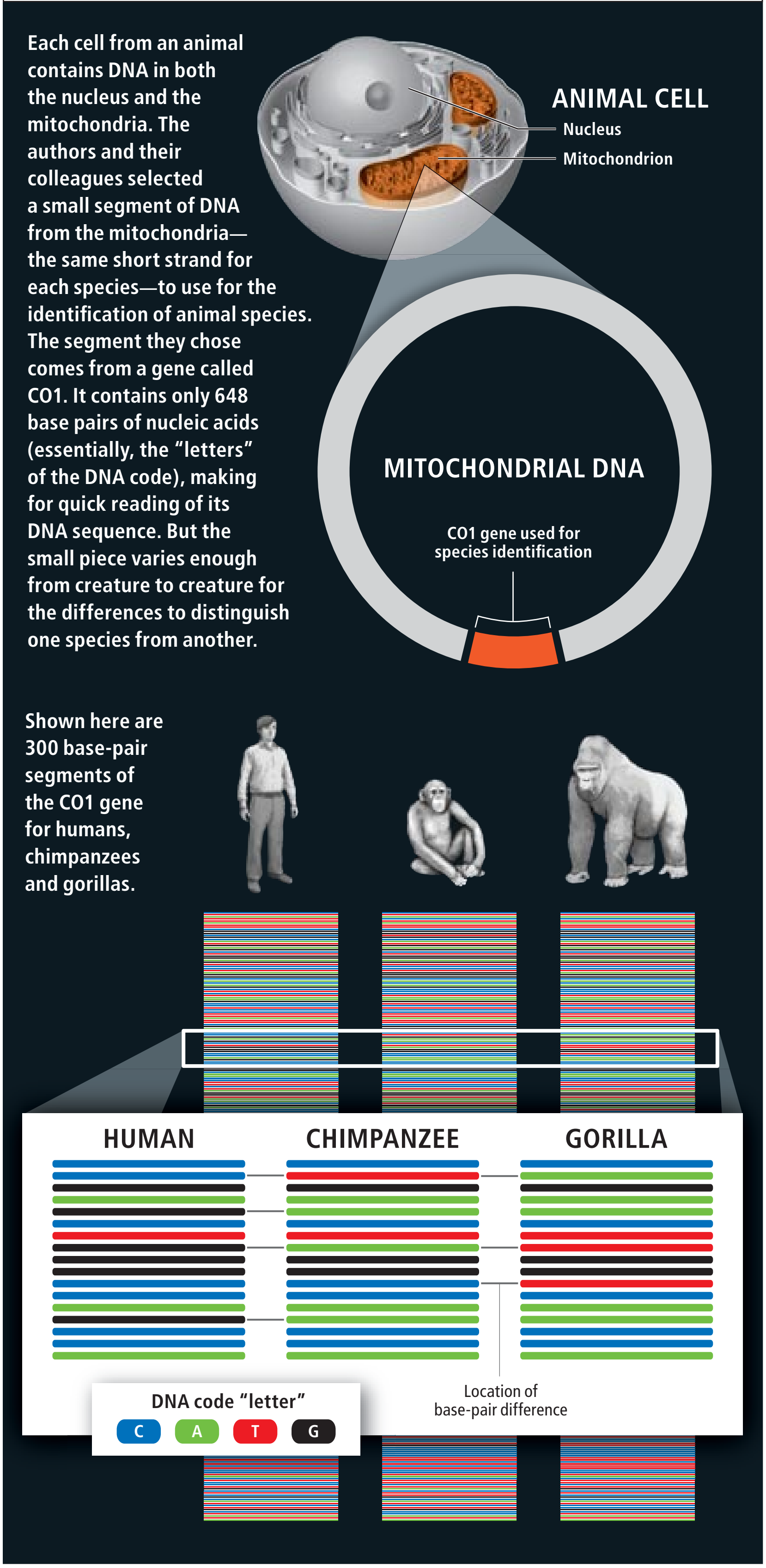
KEY CONCEPTS

- Traditional methods for classifying plants and animals demand great skill and time. Examining a small portion of the DNA is faster and easier.
- This new method is called barcoding, because it was inspired by the barcode on products.
- The authors propose that a segment of mitochondrial DNA can distinguish animal species. They imagine a day when a handheld scanner (similar to a GPS device) will link to a database of the barcodes of all species. Then, by inserting a snippet of tissue into the scanner, anyone can get an instant identification of a creature or plant.

—The Editors

[HOW BARCODING WORKS]

STREAMLINED GENETICS



taxonomic experts are needed to identify specimens from a single biodiversity survey. Finding appropriate experts and distributing specimens can be time-consuming and expensive. Web-based databases with high-resolution images help with the logistics to some extent, but other problems persist.

For example, biologists estimate that some eight million species have not yet been described, and as the encyclopedia of morphological characterizations expands, simply determining whether a specimen matches a known species will become increasingly difficult. Furthermore, eggs and juvenile forms, which are often more abundant than adults, may have no distinguishing characteristics and must be reared to maturity (if that is possible) to be identified. In some species, only one sex can be identified. For plants, a specimen may be readily classified from flowers, whereas roots and other vegetative parts are indistinguishable. A quick and easy standardized method of using genetic information could bridge these problems.

Making It Work

The first step toward discovering whether a pared-down method of using genetic information made sense was finding a short piece of the DNA that could actually deliver identifications—one that was long enough to contain information that would distinguish species but short enough to be fast and efficient to use. After some trial and error, we were able to settle on a particular gene segment as the standard reference for animal species. (Plants are another story [*see sidebar at top of opposite page*].) This segment is part of a gene housed in mitochondria—energy-producing subunits of cells, which are inherited from the mother. The gene we selected gives rise to an enzyme called cytochrome *c* oxidase subunit 1, or CO1 for short. The CO1 barcode region is small enough that the sequence of its nucleic acid base pairs (the "rungs" of the famous double helix) can be deciphered in one read with current technology. And although it is a tiny fraction of the DNA inside each cell, it captures enough variation to tell most species apart.

In primates, for example, each cell has about 3.5 billion base pairs. The CO1 barcode is only 648 base pairs long, yet examples taken from humans, chimpanzees and the other great apes harbor enough differences to distinguish the groups. Humans vary from one another at one or two base pairs in the barcode region, but we

TOMMY MOORMAN (*illustrations*); SOURCES: CORIELL INSTITUTE FOR MEDICAL RESEARCH (*chimpanzee and gorilla sequences*); BIODIVERSITY INSTITUTE OF ONTARIO (*colored barcodes*)

diverge from our closest relative, chimpanzees, at approximately 60 sites and from gorillas at about 70 sites.

Mitochondrial DNA proved especially suitable, because sequence differences among species are much more numerous than in the DNA of a cell's nucleus. Thus, short segments of mitochondrial DNA are more likely to parse separate species. In addition, mitochondrial DNA is more abundant than nuclear DNA and therefore easier to recover, especially from small or partially degraded samples.

To prove that this small DNA tag could actually identify a species, we, along with our colleagues, have tested the effectiveness of the CO1 barcode in diverse animal groups from land and sea, from the poles to the tropics. We have found that CO1 barcodes by themselves distinguish about 98 percent of species recognized through previous taxonomic study. In the remainder, they narrow identification to pairs or small sets of closely allied species, generally lineages that only recently diverged or species that hybridize regularly.

Now that we have found a barcode, the next step is to compile a reference library of this segment from specimens whose identity is already firmly established. By comparing barcode DNA from some creature against these "voucher specimens," researchers can determine whether the organism is a member of a known species or is a new find. The mechanics of creating the library are simple: someone obtains DNA from a tissue sample, determines the base-pair sequence of the barcode segment, and enters the information into a barcode database. The acquisition of specimens is more complex. The extent of variation within each species, though low, nonetheless suggests that at least 10 individuals per species should be analyzed to register this diversity. Even though the world's museums hold more than 1.5 billion specimens, most were not prepared with DNA recovery in mind, and many are simply too old to yield full barcode sequences. For older museum specimens that serve as original references for taxonomic names, amplifying a mini barcode of 100 to 200 base pairs, a size that can often be recovered from old or damaged DNA, will usually provide enough information to demonstrate membership in the same species as younger specimens with full barcodes. To aid construction of the barcode library, researchers at many institutions have begun assembling large tissue banks stored under conditions that preserve DNA.

Keeping track of so many specimens and their sequences is an engineering challenge in itself. But the process has already begun with the

THE UNIQUE CHALLENGE OF PLANTS

The gene used for barcoding animals is not practical for plants, because the plant genome has evolved quite differently. Also, an inability for two groups to mate productively with each other commonly defines animals as separate species, but many plant species can hybridize, which blurs their genetic boundaries. Scientists from museums, universities and botanical gardens around the world are now testing several highly promising gene segments that might serve as a barcode for all plant life.

[PRACTICAL USES]

BARCODING IN THE REAL WORLD

Once a handheld barcode reader is available for examining a tissue sample and is connected to a database, scientists foresee many practical uses:

- Biologists could identify organisms in the field to quickly assess biodiversity.
- Public health authorities ▸ could identify mosquitoes carrying infectious agents, such as West Nile virus, and other disease vectors, enabling timely application of targeted control methods.

- Restaurant owners and consumers ▸ could check fish to be sure what they are buying is what is advertised.

- Taxonomists could spot genetically distinct specimens, speeding up cataloguing of new species before they become extinct.
- Farmers could identify pest species invading their fields, and port inspectors could intercept shipments harboring harmful species at borders.
- Doctors could rapidly diagnose fungal pathogens and parasites, such as the one that causes malaria.
- Museums could ▸ analyze the large backlogs of collected specimens, helping them find undescribed species lurking in museum drawers.

- Regulatory agencies could test animal feed for forbidden items likely to spread illnesses such as mad cow disease.

TOMMY MOORMAN (*leaf*); NOAH PORITZ *Photo Researchers, Inc.* (*mosquito*); SCOTT CAMAZINE *Photo Researchers, Inc.* (*bugs*); TOM HOPKINS *Aurora Photos* (*fish fillets*)

[CASE STUDY]

PARSING BUTTERFLIES

Caterpillars (*photographs, below left*) of the skipper butterfly (*Astraptes fulgerator*) in Costa Rica differ in appearance, habitat and favored foods, but the adults all look very similar (*below right*), and scientists had long thought they belonged to a single species. Barcoding tells a different story, however. Because variation in the CO1 gene correlates with appearance, lifestyle and chosen foods of the caterpillars, researchers determined that, despite the outward appearance of the adults, the butterflies actually divide into 10 separate species.

[THE AUTHORS]

Mark Y. Stoeckle (***left***) **is an adjunct faculty member in the Program for the Human Environment at the Rockefeller University. A graduate of Harvard Medical School, he is also clinical associate professor of medicine at Weill Medical College of Cornell University. He is an accomplished nature photographer. Paul D. N. Hebert (*right*), best known for founding the concept of DNA barcoding, completed a Ph.D. in genetics at the University of Cambridge and currently holds a Canada Research Chair at the University of Guelph, where he also directs the Biodiversity Institute of Ontario. In his free time, he enjoys chasing small life in exotic places—gathering moths in Australia is his current favorite.**

establishment of a public database called the Barcode of Life Data systems, or BOLD (online at www.barcodinglife.org). BOLD now has over 460,000 records from more than 46,000 species spanning the animal kingdom, with particularly dense records for birds, fishes, butterflies and moths. Each of these records contains the species name, barcode sequence, collection location, links to the voucher specimen, photographs and other biological data. To help coordinate the enormous effort involved in the assembly of such a comprehensive library, the Consortium for the Barcode of Life (CBOL) was established in 2005; it includes 150 institutions from 45 countries that support the development of DNA barcoding as a global standard for the identification of species. The actual assembly of records will be driven by the International Barcode of Life Project: a 25-nation alliance that plans to process five million specimens from 500,000 species by 2014.

What We Have Learned So Far

As E. O. Wilson points out, despite 250 years of effort we do not know, even to the nearest order of magnitude, how many species live on earth. DNA barcoding is already helping to speed cataloguing of biodiversity. One of the major findings so far is that there are more species—each more narrowly specialized—than scientists had realized. This revelation has come about through new information that barcoding has provided on so-called cryptic species, organisms that look alike but show genetic differences indicating they are separate species.

DNA barcode surveys have revealed cryptic species lurking in museum drawers in every group studied so far. For example, Hebert, together with Daniel Janzen, a biodiversity ecologist at the University of Pennsylvania, and John Burns, a taxonomist at the Smithsonian Institution, and their colleagues in Costa Rica, found that what was thought to be one species of skipper butterfly, *Astraptes fulgerator,* was actually at least 10 different species [*see box above*]. Because the adults are extremely similar, scientists did not realize they were so different genetically. Similarly, Alex Smith of the Biodiversity Institute of Ontario and his colleagues discovered that three morphologically recognizable species of flies that parasitize diverse insects are in fact an assemblage of 15 species, with each lineage specializing on a few hosts. Work by one of us (Stoeckle) showed that even in a very intensively studied group, North American birds, about 4 percent of named species contain genet-

CATHERINE HART (*Stoeckle*); B. ST. JACQUES (*Hebert*); DANIEL JANZEN *University of Pennsylvania (caterpillars and butterfly)*

ically distinct lineages that are likely to be separate species.

One of the most striking early findings is the surprisingly low level of mitochondrial genetic diversity within most animal species. This discovery confounds a prediction from population genetics theory that older or larger populations should show more diversity. Low levels of variation are often thought to indicate recent population bottlenecks. For example, scientists thought the relative absence of mitochondrial variation in human populations indicated a near-extinction of early humans in eastern Africa 150,000 years ago. According to this hypothesis, all modern humans trace their origin to a single female from this time, the so-called mitochondrial Eve. The discovery that similarly impoverished levels of genetic diversity are the rule across the animal kingdom raises doubts about the Eve hypothesis and presents a larger unsolved scientific question: What forces limit mitochondrial diversity within species? We and others believe that the consistently low levels of sequence divergence reflect frequent "selective sweeps," in which new, advantageous mutations displace ancestral variation, pruning diversity within species.

Our research so far has demonstrated that barcoding can speed up the survey of biodiversity. The fact remains, however, that formal descriptions of new species can take years to complete. The generation of sequence data is thus running far ahead of official species descriptions. We view barcoding as creating a map of DNA diversity that will serve as a framework for subsequent detailed study. Just as the speed and economy of aerial photography caused it to supplant ground surveys as the first line of land analysis, DNA barcoding can be a rapid, relatively inexpensive first step in species discovery. The "ground truthing" will take more time. But linking these approaches will produce an integrated view of the history and present-day existence of life on earth and help to shepherd life's full magnificence into the coming centuries. ■

[CONTROVERSY]

The Authors Answer Some Common Concerns

A big science initiative such as barcoding will make funding even more scarce for already underfunded disciplines such as taxonomy.

There is no evidence that barcoding is draining away support. On the contrary, the sources of funding for barcoding, including private foundations (Alfred P. Sloan Foundation, Gordon and Betty Moore Foundation) and government agencies (Genome Canada), are new sources of funding for taxonomy.

DNA barcodes frequently cannot distinguish between closely related or recently diverged species.

Very young species that cannot be distinguished by DNA barcoding make up a small fraction of species and are often difficult to separate by traditional methods as well. Some of these cases represent single species incorrectly split or species in the process of formation, and DNA barcoding can help flag such cases for taxonomic review.

The mitochondrial gene used as a barcode does not differentiate accurately between all animal species and does not work at all for some taxonomic groups.

Taxonomic groups demonstrating effectiveness of barcodes include bats, bees, chitons, clams, copepods, fish, frogs, fruit flies, mayflies, nematodes, spiders, sponges and springtails. Results so far show there are very few animal groups not well distinguished by DNA barcodes. In fact, many animal species cannot be distinguished by traditional methods or require expensive equipment or advanced training, and yet they are readily identified by DNA barcoding.

Barcoding is not really new; it is just a marketing device.

The underlying concept goes back 30 years to Carl Woese of the University of Illinois, who first showed that DNA sequences could be used to reconstruct the Tree of Life. But the idea of establishing an identification system for all plant and animal life using genetic sequences from a uniform locus was first proposed in 2003, and the DNA barcode reference libraries have begun to accumulate only in the past three to four years. What is also new, and what makes the system work, is attaching a uniform set of data to each barcode record.

MORE TO EXPLORE

The paper that launched a thousand barcoders: **Biological Identifications through DNA Barcodes.** Paul D. N. Hebert, Alina Cywinska, Shelley L. Ball and Jeremy R. deWaard in *Proceedings of the Royal Society B*, Vol. 270, No. 1512, pages 313–321; February 7, 2003. Available at **http://journals.royalsociety.org**

The Barcode of Life Data systems is a workbench for researchers, with public links to published projects, an "identification engine," a taxonomy browser, Google maps, and more: **www.barcodinglife.org**

Consortium for the Barcode of Life (CBOL), an international initiative devoted to developing DNA barcodes as a global standard for the identification of biological species, is based at the National Museum of Natural History: **www.barcoding.si.edu**

Mark Y. Stoeckle's DNA Barcode Blog is a weekly illustrated scientific blog about short DNA sequences for species identification and discovery: **http://phe.rockefeller.edu/barcode/blog**

With OPEN-SOURCE ARMS

A community of engineers, designers and innovators is collaborating online to make better prosthetic hands and arms for amputees. One of the lead engineers lost his own arm in Iraq

By Sam Boykin

KEY CONCEPTS

- With enhanced emergency medicine, many soldiers are coming home from war with grievous injuries instead of being killed.
- Innovation in arm and hand prostheses has been slow because the market for the devices is small and development costs are high.
- The Open Prosthetics Project (OPP) has applied the "open source" model—long used in developing "community-based" software—to the design of inexpensive prosthetic hands and arms that a small demand can still support. The designs are free for anyone to use.

—The Editors

Before Jonathan Kuniholm, a marine reservist, was shipped off to the war in Iraq, he and three friends formed a research and development firm they called Tackle Design. The four men had worked together in an industrial engineering class at North Carolina State University (N.C.S.U.), and, filled with youthful enthusiasm, they hoped their fledgling company could survive on jobs that were interesting and beneficial rather than simply moneymaking. They worked with inventors—making prototypes for a plastic lock to keep shoestrings tied and a fishing lure with an embedded LED—as well as with medical engineers from their alma mater, who were developing tools for minimally invasive robotic surgery.

Then, before business had a chance to get off the ground, Kuniholm was deployed. A few months later, on New Year's Day 2005, he and about 35 other marines were ambushed near the Hadithah Dam along the Euphrates River northwest of Baghdad. His platoon had been looking for insurgents who had fired at a Swift boat patrolling around the dam a few hours earlier. As the marines closed in on the suspected hotspot, an IED—improvised explosive device—hidden in a can of olive oil exploded. Shrapnel ripped through the platoon, and Kuniholm was blasted off his feet. Moments later, when he came to his senses, he discovered his M16 rifle had been blown in half and his right arm was nearly severed just below the elbow. Caught in a raging firefight, Kuniholm pulled himself out of harm's way. His fellow marines called for air evacuation, and soon surgeons at a hospital near Baghdad were amputating his ravaged arm.

After returning to North Carolina, Kuniholm underwent multiple surgeries at the Duke University Medical Center. Then, following his convalescence, he visited Walter Reed Army Medical Center in Washington, D.C., where doctors outfitted him with two kinds of artificial replacement for his hand and lower arm. One was a conventional split-hook device, essentially two hooks aligned with each other, which the user can spread apart or close up via a harness and cable system activated by the shoulder or arm [*see hook in box on page 74*]. The second was a more advanced "myoelectric" prosthesis, which picks up nerve signals produced by the slightest muscle tension and translates the signals into movement. Flexing the upper arm mus-

THE OPEN PROSTHETICS PROJECT (*Trautman hook*)

cle causes the pincers of a prosthetic "hand" to grip; relaxing the muscles causes the pincers to release.

The two prostheses from Walter Reed were state-of-the-art, the latest in prosthetic design. But back in North Carolina, Kuniholm and his partners at Tackle Design were shocked at the lack of innovation in arm and hand prostheses. They were sure they could do better. And that is how the small North Carolina design firm got into the prosthetics business. More, Kuniholm and his partners have created a clearinghouse for prosthetic designs, an online consortium they call the Open Prosthetics Project (OPP), whose goal is to nurture useful ideas for innovations and then freely give the designs away. The idea is to benefit not only people such as Kuniholm, who already have the resources that come from living in a first-world economy, but also amputees all over the world.

Innovation Stagnation

Ironically, one of the reasons a group such as the OPP can get on the public radar at all is the high human cost of the wars in Iraq and Afghanistan. Because of tremendous advances in emergency medicine, as well as the use of such armor as Kevlar vests, the fighting has resulted in a far lower fatality rate among injured soldiers than it has in past wars. That's the good news. The bad news is that many veterans whose wounds would have killed them in the past come home today with grievous injuries.

Still, in absolute terms, the number of upper-limb amputees is small, and the prosthetics market is hard to crack. As Kuniholm and his partners did their research about the prosthetics industry, it became evident that the main reason for the lack of innovation was a lack of financial incentive. According to the Amputee Coalition of America, 1.7 million Americans have lost a limb because of illness or trauma, but relatively few of them need a replacement arm or hand. The typical amputee is older than 50 and has lost a leg or a foot to diabetes or some other disease. Upper-extremity amputees—those who have lost an arm or a hand—number about 100,000 people, or some 6 percent of the total. Fewer still are wounded veterans. As of the end of 2007, about 700 veterans of the wars in Iraq and Afghanistan are amputees, and of those about 150 have lost a hand or an arm (or, in some cases, both arms).

Such a relatively small market, and the resulting narrow profit margins, makes it unprofitable for most companies to invest in research and

OPEN-SOURCE collaboration has extended from software development to the design and prototyping of such useful objects as a prosthetic hand. Here a prosthesis called the Trautman hook has become the focal point of an online discussion intended to improve and update it.

SLIM FILMS

[BY THE NUMBERS]

THE NEED FOR NEW ARMS

- **150** veterans of the wars in Iraq and Afghanistan were missing arms or hands by end of 2007
- **100,000** upper-limb amputees live in the U.S.
- **650,000** people are upper-limb amputees worldwide; most of those who live in the developing world need arm or hand prostheses

JONATHAN KUNIHOLM, an engineer and Ph.D. candidate in biomedical engineering at Duke University, organized the Open Prosthetics Project to improve artificial arms and hands. Kuniholm works from personal experience: he lost part of his right arm in the Iraq War.

development of upper-arm prostheses. "Prosthetics is one of many underserved markets in which innovation has stagnated because the traditional incentives are lacking," Kuniholm says. "The people who make innovations in this field are usually passionate users tinkering around in their garage."

What Kuniholm has in mind is what Eric von Hippel calls a lead user—a person who is out in front of most other people and even other companies with respect to an important market trend. A lead user also expects to reap great profits or benefits from the trend. According to von Hippel, a professor and head of the Innovation and Entrepreneurship Group at the M.I.T. Sloan School of Management, lead users also tend to be active innovators. Kuniholm is betting that by incorporating the insights of lead users into a new product, the product has a good chance to win in the marketplace because it anticipates consumer needs.

But patenting and securing a manufacturer are costly and convoluted processes, so most amputees who try to improve prosthetic designs never see their ideas get past the workshop. "All that information and innovation mostly just disappear into the ether," Kuniholm adds.

The Web site www.openprosthetics.org, which is part of an organization called the Shared Design Alliance, invites prosthesis users, engineers and anyone else with an interest to join a discussion entitled "Pimp My Arm." (The name is a takeoff on the MTV show *Pimp My Ride,* which features auto mechanics who fix up and customize old clunkers.) Participants can contribute time, hunches and imagination about how to improve the devices. All the ideas are "open source"—that is, nothing is proprietary, and any idea is understood to be freely shared.

A Simple Solution

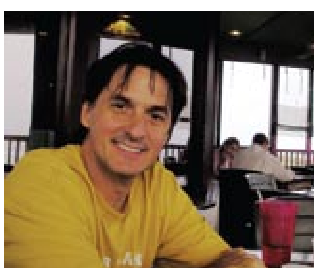
Kuniholm's chief personal contribution to the OPP is the ongoing development and improvement of the Trautman hook [*see box on opposite page*]. Introduced in 1925, the device is classified as a "voluntary opening" prosthesis, meaning its pincers are held closed with internal rubber bands. If the user wants to open the hook, he moves or shrugs his shoulder, which engages a harness and cable system. If that sounds relatively crude and basic, it is. Like most other hooks on the market, the Trautman design has changed very little since it was first introduced. "Many prosthetics manufacturers are subject to the same one-size-fits-most economics as mass-market consumer goods," Kuniholm says. But in prosthetics, he adds, "each person's needs and capabilities are unique."

Although hooks may not be aesthetically pleasing and are decidedly low tech, they are generally more functional and durable and certainly less expensive than myoelectric devices (hooks cost between $600 and $2,200, on average, whereas myoelectric hands start around $6,000). Moreover, the Trautman hook is unique in having a so-called back lock: like the ice tongs once used for carrying blocks of ice, which convert the weight of the block into the force that grips both its sides, the pincers of the hook lock or squeeze harder on an object as the user pulls back on the hook with greater force. Another advantage is that the pincers of the Trautman hook have serrated teeth that interlock, making its grip even stronger.

"There are many options for prosthetic devices, but none with this one's capabilities," says Agnes A. Curran, an upper-extremity specialist and clinical director of the Orthotic and Prosthetic Group of America. "Throughout my travels I meet patients all over the country who are longtime Trautman hook users, and these guys won't even look at a modern device. They keep them held together with welds, baling wire and duct tape."

Because of its unique features and rugged design, the Trautman hook developed a passionate following, particularly among farmers and ranchers in the Midwest. But the manufacturer, the Paul Trautman Company, went out of business in the 1990s, and within a short time after the company's demise, only a limited number were still available on the aftermarket. When

[THE AUTHOR]



Sam Boykin is a prizewinning journalist based in Mooresville, N.C. His writing has appeared in *Car and Driver, Consumer's Digest, Entrepreneur, Reader's Digest* and the online magazine Salon.com.

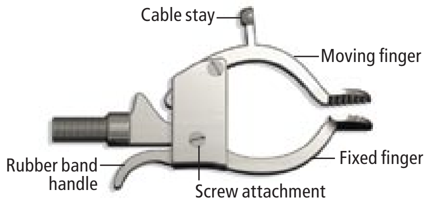
KIMIKO JENNINGS (*Boykin*); ANDREW SYNOWIEZ *synster.com* (*Kuniholm*)

[HOW IT WORKS]

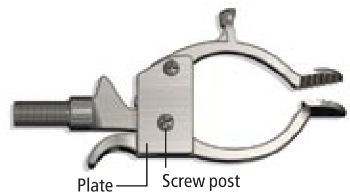
UPDATING A CLASSIC

Invented in 1925, the Trautman hook is robust, simple and cheap, and it remains the replacement prosthesis of choice among many hand or arm amputees. When its manufacturer, the Paul Trautman Company, went out of business in the 1990s, users continued to trade and mend their old hooks. Tackle Design reverse-engineered the device and then focused on strengthening the hook in areas that users reported as common failure points.

ORIGINAL DESIGN

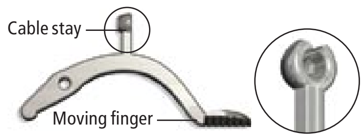


NEW DESIGN



Cable stay

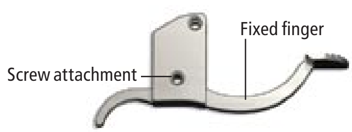
PROBLEM:
Frequent breaks where cable stay attaches to moving finger



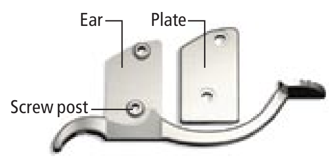
SOLUTION:
Increase cross-sectional area of cable-stay attachment; add rib to base of cable stay to better distribute the load

Screw attachments

PROBLEM:
Constant rotation between fixed and moving fingers on screw attachment causes screw to ream out the threads in the hole; device seizes, however, if screws are tightened down



SOLUTION:
Add screw posts; sandwich both fingers between ear and plate. Moving finger thus rotates on screw post instead of on a screw; gap between ear and plate is fixed even if screws are overtightened



SLIM FILMS

Kenneth M. Heide, a prosthetist in Fargo, N.D., who has many patients loyal to the Trautman hook, heard about the OPP, he saw it as the perfect opportunity to get the unique device back on the market. With the blessing of the Trautman company, Heide loaned the OPP two old Trautman devices borrowed from his patients and two new devices from Steven Stolberg, an instructor at Century College in White Bear, Minn., who used them in his class. Tackle Design reverse-engineered them, creating a digital model in a computer-aided design (CAD) program that could serve as a starting point for making improvements.

For the first batch, Kuniholm and his partners kept it simple. All they did was make some small changes to strengthen the used hooks where they had broken and then been welded back together. They e-mailed the specifications of one of the hooks to Anvil Prototype & Design in Charlotte, N.C., which put the digital designs through a process called rapid prototyping. Anvil transformed the digital information into the specifications for a "3-D printer" to build an early-stage concept model out of thousands of thin layers of powder and binder materials, adding or "printing" them one layer at a time. Rapid prototyping makes it possible to refine the design quickly. Rapid Tool in Boulder, Colo., then made four test models out of a bronze-infused stainless steel powder that was also added layer by layer, heated and fused. Tackle Design donated the new and improved hooks to patients for a test run.

Testing, Testing

One of the test patients was L. Gus Davis, the 57-year-old president of a water treatment company in St. Peter, Minn., who lost his right arm in a 1972 motorcycle accident. Although Davis had once considered getting a myoelectric arm, he thought it could never withstand his lifestyle. "I still ride motorcycles, I run a chain saw and I split wood by hand," Davis says. "I'm pretty hard on [prosthetic devices], and I don't think the myoelectric could stand up to it. But the Trautman hook is slick and tough. I would definitely be a potential customer."

With feedback from his test patients, Kuniholm is fine-tuning the design of the next round of prototypes. He says the simplicity of the original hook—three metal parts and two screws—makes it a promising candidate for further customization and improvement. It could be made of a lighter alloy, for instance, and it could probably be modified to have a stronger grip. But the main glitch has already been fixed. For the hook to open and close properly, one of the screws had to be loosened, and with time that enlarged the hole and allowed the screw to wiggle free. To remedy the problem, many longtime users drilled out the screw holes, welded metal into them and tapped in new threads for the screws. Eventually, though, repeated repairs put a lot of wear and tear on the hook. Two students at N.C.S.U., Andy Richards and Richard Shoge, modified the design to correct the problem [*see box above*].

Eagerly awaiting the next test batch is Curran. Many of her patients were veterans of World

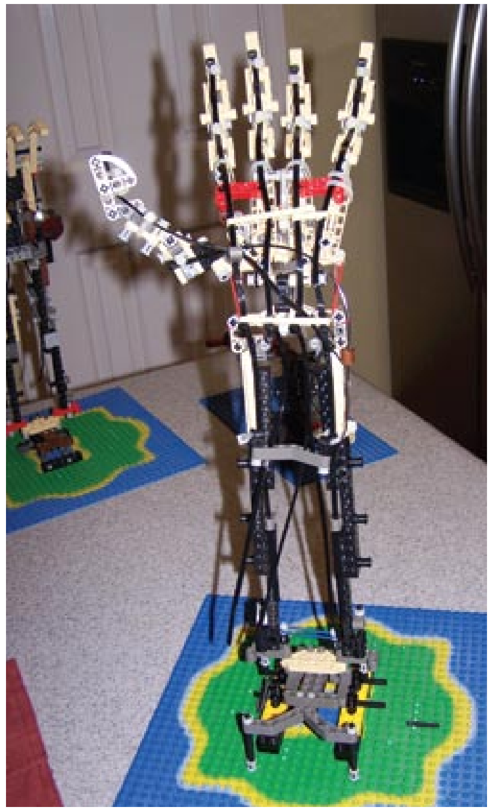
War II, and most of them, elderly and accustomed to what they had, made little demand for prosthetic innovation. But recently she has started to see a growing number of younger patients, particularly soldiers returning from Iraq. "I would love to see what the younger guys think of this device and let them compare it with the more modern ones," she says.

In addition to helping people here in the U.S., a cheap and simple device such as the Trautman hook would be invaluable in developing countries, where war, poor health care and manual labor are common. In such areas the population of upper-limb amputees is growing at an alarming rate, and a prosthesis can be crucial for returning to gainful employment. Yet a severe lack of funds prevents most amputees from receiving a simple, cheap and durable prosthesis. "We have to think outside the U.S.," Curran says. "We need to look at places like Saudi Arabia, India, China, Sierra Leone, Bangladesh and elsewhere in the world where, unfortunately, some of the amputations are punitive."

It's the Economy, Stupid

The key to getting the hooks into the hands of the people who need them is finding a distributor that is willing to market the hooks internationally. But that has proved to be more easily said than done.

"When I was going around to different companies asking if they'd be willing to help out, they all asked the same question," Curran says. "'How many will I sell in a year?' If there's not a lot of potential profit, they're just not that interested." And with plenty of options already available, what point is there in trying to come up with another device, particularly in a market so fraught with financial obstacles?



PROTOTYPE of an artificial hand has been put together out of inexpensive plastic snap-together Lego blocks by John Bergmann, a volunteer at Tackle Design. Each finger can be curled or extended independently of the others; the wrist can be bent and twisted naturally. The Lego parts offer a rapid and flexible way to experiment with complex, novel designs.

ARMS AND THE ATHLETE

Modular attachments, such as the basketball "paddle" worn on the left arm of the player at the far left, can convert an artificial arm into specialized equipment. Customized attachments are also available for:

- Baseball
- Billiards
- Cycling
- Golf
- Hockey
- Shooting
- Skiing
- Softball
- Tumbling
- Weight lifting

To Kuniholm, that is the counsel of despair. You might just as well say that everything that needs to be invented already has been. To be sure, there are plenty of prosthetic devices available that do different things well. "But," he notes, "there's still nothing on the market that's an acceptable substitute for a hand."

William J. Hanson, president of Liberating Technologies, Inc. (LTI), in Holliston, Mass., a manufacturer and distributor of upper-limb prosthetic components, explains that his company distributed the first titanium split hooks in the U.S. Like most prosthetics companies, though, LTI shifted its focus away from hooks and on to more modern mechanical and myoelectric devices. "Now just a handful of well-established companies supply most of the market with body-powered hook devices," Hanson says.

Hosmer Dorrance Corporation is one of those companies. Based in Campbell, Calif., Hosmer is one of the leading manufacturers of upper- and lower-extremity prostheses. Karl Hovland, the company's president, recalls that over the years many inquires have come in about the Trautman hook. It has always remained on the back burner, he adds, because it never promised a big enough return to make the investment: "We would certainly consider it, but the numbers have to add up." Making such an invest-

THE OPEN PROSTHETICS PROJECT (*Lego prototype*); DEREK MONTGOMERY *AP Photo* (*basketball players*)

ment even more risky is that Medicare recently consolidated its reimbursement billing system for "orthotic and prosthetic" services. The result has been smaller reimbursements for several kinds of functional hooks. "There's just no incentive if the reimbursement is less than what we have to charge for them," Hovland says. "We want to do everything we can for the patient, but we are a business for profit."

And therein lies the rub. Kuniholm's vision of "substituting public good for profits" keeps running up against bottom-line roadblocks. Nevertheless, Kuniholm, who is pursuing a Ph.D. in biomedical engineering at Duke University, continues to search for manufacturing, marketing and distribution channels for the Trautman hook. He hopes to find a company that will donate e-commerce and payment and order management services—or better yet, a company already developing prosthetic devices that is willing to take on the OPP designs.

"The reality," he notes, "is that there's no traditional economic incentive to do work and make improvements on prosthetics. That doesn't mean that nobody cares, but most people don't have the money or know-how to magnify whatever efforts or improvements they make. I think we can generate far more societal benefit if we give away information than if we commercialized and sold the ideas. Our goal is to create a way to share these efforts and improvements with anyone who needs them." ■

HOOKS VS. HIGH TECH

Advanced artificial arms and hands display almost human-like motions, but despite press reports, thought-controlled units are not yet available. To many patients, however, the high-tech devices remain too slow, heavy, costly, fragile or hard to control to be practical.

- Nerve-controlled (myo-electric) artificial arms, long available commercially, translate nerve signals from muscle contractions within the stump into movements.
- Advanced hand and arm prototypes built by Dean L. Kamen of DEKA Research and Development Corporation and by the Defense Advanced Research Projects Agency (DARPA) can pick up a pen, scratch a nose or pour water into a glass.

[OPEN SOURCE]

Many Heads Are Better Than One

The Open Prosthetics Project (OPP) has extended online collaboration from software development to the design and testing of several devices in addition to the Trautman hook. A few examples:

BODY-POWERED HARNESS

A cheap, washable harness sewn into an elastic, moisture-wicking T-shirt, for connecting to the cable that controls the action of a hook or gripping prosthesis.

SOME GOALS FOR ONLINE COLLABORATORS:

- Devise a strong but comfortable way to attach the harness to a T-shirt
- Develop a simple way for the user to attach the harness to the cable

SPLIT HOOK

A "double" hook that can grip and release when a cable mechanism changes the gap between the two hooks.

SOME GOALS FOR ONLINE COLLABORATORS:

- Design an updated version that can be made of light plastics and without metal (for wearing through airport security)
- Cut manufacturing cost to less than $150
- Provide grip surfaces that provide the greatest flexibility to the user

VECTOR PREHENSOR

A simple means of adjusting the closing force of the rubber band or spring that opposes the user's pull on a cable that opens a split hook or gripper.

SOME GOALS FOR ONLINE COLLABORATORS:

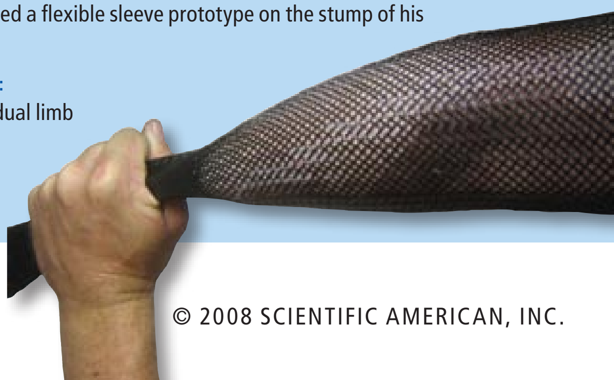
- Minimize manufacturing costs
- Devise a kit that would enable existing hooks to be retrofitted

SUSPENSION SYSTEM

A way of attaching a prosthesis to the body of an amputee based on the principle of the "Chinese finger trap." The trap works because woven or braided material contracts along one axis as it expands on the other. Jonathan Kuniholm has tested a flexible sleeve prototype on the stump of his own severed arm.

SOME GOALS FOR ONLINE COLLABORATORS:

- Get a grip on the shortest possible residual limb
- Wick moisture away from the skin
- Adjust the braid for optimum ratio between pulling and contracting forces



THE OPEN PROSTHETICS PROJECT

➥ MORE TO EXPLORE

One-Handed in a Two-Handed World. Second edition. Tommye-Karen Mayer. Prince-Gallison Press, 2000.

Democratizing Innovation. Eric von Hippel. MIT Press, 2005. An electronic version of this book is available for download at **http://web.mit.edu/evhippel/www/democ1.htm**

For more information about the Open Prosthetics Project, go to **http://openprosthetics.wikispot.org/Front_Page**

For an explanation of the many varieties of rapid prototyping as a means to cut the design and development time for a new 3-D object, go to **http://en.wikipedia.org/wiki/Rapid_prototyping**

For a video demonstration of the robotic arm built by Dean L. Kamen, go to **www.youtube.com/watch?v=1hzRja9eunY**

Outcalculating the Competition

How did self-replicating molecules come to dominate the early earth? Using the mathematics of evolutionary dynamics, Martin A. Nowak can explain the change from no life to life BY HEATHER WAX

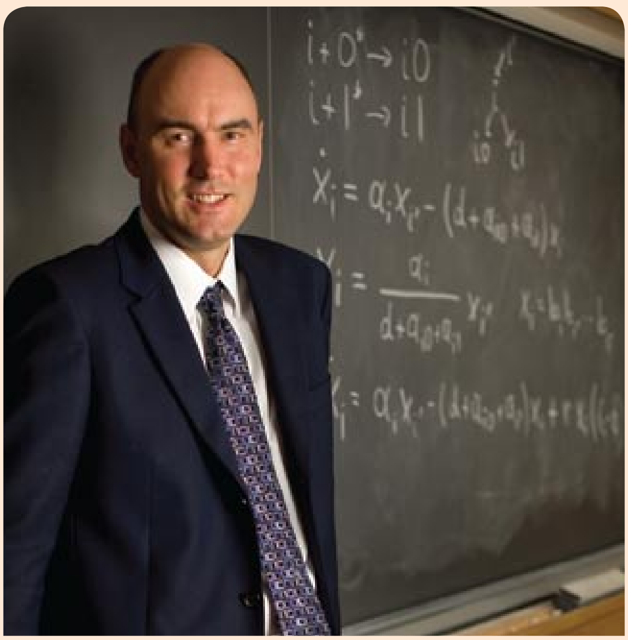
Back in March the press went crazy for Martin A. Nowak's study on the value of punishment. A Harvard University mathematician and biologist, Nowak had signed up some 100 students to play a computer game in which they used dimes to punish and reward one another. The popular belief was that costly punishment would promote cooperation between two equals, but Nowak and his colleagues proved the theory wrong. Instead they found that punishment often triggers a spiral of retaliation, making it detrimental and destructive rather than beneficial. Far from gaining, people who punish tend to escalate conflict, worsen their fortunes and eventually lose out. "Nice guys finish first," headlines cheered.

It wasn't the first time Nowak's computer simulations and mathematics forced a rethinking of a complex phenomenon. In 2002 he worked out equations that can predict the way cancer evolves and spreads, such as when mutations emerge in a metastasis and chromosomes become unstable. And in the early 1990s his model of disease progression demonstrated that HIV develops into AIDS only when the virus replicates fast enough so that the diversity of strains reaches a critical level, one that overwhelms the immune system. Immunologists later found out he had the mechanism right [see "How HIV Defeats the Immune System," by Martin A. Nowak and Andrew J. McMichael; SCIENTIFIC AMERICAN, August 1995]. Now Nowak is out to do it again, this time by modeling the origin of life. Specifically, he is trying to capture "the transition from no life to life," he says.

Trained as a biochemist, the 43-year-old Nowak believes that mathematics is the "true language of science" and the key to unlocking the secrets of the past. He began exploring the mathematics of evolution as a graduate student at the University of Vienna, working with fellow Austrian Karl Sigmund, a leader in evolutionary game theory. Evolutionary dynamics, as Nowak named the field, involves creating formulas that describe the building blocks of the evolutionary process, such as selection, mutation, random genetic drift and population structure. These formulas track, for example, what happens when individuals with different characteristics reproduce at different rates and how a mutant can produce a lineage that takes over a population.

At the home of the Program for Evolutionary Dynamics at Harvard, the blackboard is chalked with equations. Nowak has been busy working on how to whittle down the emergence of life into the simplest possible chemical system that he can describe mathematically. He uses zeroes and ones to represent the very first chemical building blocks of life (most likely compounds based on adenine, thymine, guanine, cytosine or uracil). Nowak refers to them as monomers, which, in his system, randomly and spontaneously assemble into binary strings of information.

Nowak is now studying



ERIK JACOBS *Jacobs Photographic*

MARTIN A. NOWAK

A BIG DEAL: Lured to Harvard University in 2003 when he was granted the school's first joint appointment between the math and biology departments.

NUMBERS GAME: Coined the term "evolutionary dynamics," which mathematically models how populations of genes, organisms and other biological entities change over time.

IN THE BEGINNING: Uses dynamical equations to probe whether the evolutionary force of selection preceded replication, a process that could explain how the polymers of life came to be.

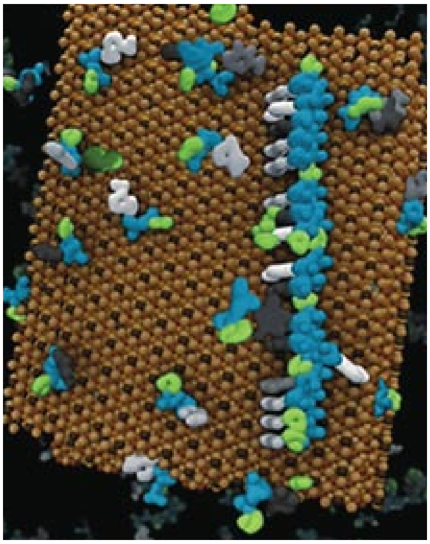
the chemical kinetics of this system, which means describing how strings with different sequences will grow. The fundamental principles of this idealized scheme, he says, will hold true for any laboratory-based chemical system in which monomers self-assemble, "in the same way as Newton's equations describe how any planet goes around the sun, and it doesn't matter what that planet is made of," Nowak explains. "Math helps us to see what the most crucial and interesting experiment is. It describes a chemical system that can be built, and once it's built, you can watch the origin of evolution."

Could it really be that simple? Right now the system exists only on paper and in the computer. Although it is easy to model mathematically, making the system in the lab is tricky because it starts without any enzymes or templates to help the monomers assemble. "It's hard to imagine an easy way to make nucleic acids," says David W. Deamer, a biomolecular engineer at the University of California, Santa Cruz. "There had to be a starting material, but we're very much into a murky area, and we don't have good ideas about how to re-create it in the laboratory or how to get it to work using just chemistry and physics without the help of enzymes."

In the 1980s biochemist Leslie E. Orgel and his group at the Salk Institute for Biological Studies in San Diego showed that a strand of RNA can act as a template for making another strand of complementary RNA—a phenomenon called nonenzymatic template-directed polymerization. Figuring out how nucleotides might self-assemble without templates, however, has proved harder. "I want a process that can comprise polymers," Nowak says.

Irene Chen, a cellular origins researcher at Harvard, says one way that monomers of RNA or DNA might form polymers in the absence of enzymes is by adding a compound called imidazole to one end of the monomers, making them more reactive and their polymerization quicker and easier. Lipids or clay might also be essential—other researchers have shown that they can help speed up the reaction. At Rensselaer Polytechnic Institute, for instance, chemist James P. Ferris induced adenine nucleotides to assemble into short polymers of RNA—strands 40 to 50 nucleotides long—on a kind of mineral clay that may have been common in the prebiotic world.

Using his mathematical model, Nowak looks at chemical reactions that lead to these kinds of strands and assigns rate constants to the reactions. That is, he imagines that strings with different binary information grow at different rates, with some taking in monomers faster than others. Then he calculates their distributions. Small differences in growth rates, he has noticed, result in small differences in abundance; sequences that grow slower are less common in the population, getting outcompeted by faster ones. "This I find great," Nowak exclaims, "because now you have selection prior to replication in a completely natural way."



ALL TOGETHER NOW: In a prebiotic earth, clay surfaces (*brown*) may have helped nucleotides (*blue* and *white*) form RNA strands.

JANET IWASA *Szostak Group, Massachusetts General Hospital/Harvard University*

Some strands mutate, and sometimes one sequence accelerates the reaction rates of other sequences, demonstrating the kind of cooperation that Nowak has long argued is a fundamental principle of evolution. Taken together, he says, the result is a lifelike chemical system ripe with evolutionary dynamics. He calls this system "prelife" because "it has the qualities of life—genetic diversity, selection and mutation—but not replication."

Typically mutation and selection are seen as consequences of replication. If suddenly, for example, only large, hard seeds were available to the finches of the Galápagos Islands, those with bigger, stronger beaks would be more likely to survive and, generation after generation, would become more common in the population. Selection for a trait, be it beak size or something else, depends on passing down the genes for that trait to offspring. But Nowak says his model shows there can be selection prior to replication—which means that maybe there is selection *for* replication. If this kind of selection is possible, he notes, maybe it can help explain the origin of life.

All that is necessary is for a few strings to suddenly develop the ability to make copies of themselves—the way some researchers believe certain strands of RNA first became dominant on the primitive earth. Enough free monomers would have to be around to make replication advantageous, Nowak points out, and the replicating strings must be able to use up the monomers faster than the nonreplicating strings. According to his calculations, only when the rate of replication went beyond a certain threshold would the equilibrium of the system change, allowing life to emerge. "Life destroys prelife," he states. "All of this happened at some stage."

Nowak hopes that his model will guide experiments. When it comes to understanding the beginning of evolution, building the chemical system he describes mathematically—a system in which only two types of monomers self-assemble and then self-replicate—"is the simplest thing you can do," he says. "Mathematics is the proper language of evolution. I don't know what the 'ultimate understanding' of biology will look like, but one thing is clear: it's all about getting the equations right." ■

Heather Wax is based in Brookline, Mass.

Competing Candidates

By Mark Fischetti

Whenever national elections occur, debates arise over which voting technology is most accurate and least susceptible to tampering. The arguments have been waged ever since mechanical machines arrived more than a century ago as an alternative to paper ballots.

Lever machines dominated U.S. polling places from the 1930s through the 1980s but are now used only in New York State, having been gradually replaced by optical scanners and touch screens. The scanners are similar to equipment used to score standardized tests. Touch screens, known as direct recording electronic (DRE) machines, operate somewhat like ATMs.

Various studies have reached disparate conclusions about which technologies more accurately count votes and which are hardest to hack, although voter mistakes are lower for DREs. New York State asserts that lever machines are as good as other technologies, but some experts disagree. A review by California, which uses a mix of options, found none to be clearly superior. Even though lab tests have shown differences, "when you factor in real-world variables, like ease of use and proper administration by poll workers, accuracy ends up being similar"—about one error in 10,000 votes, says Douglas W. Jones, a computer science professor at the University of Iowa and an expert on voting technology.

Better ballot design could also reduce mistakes. "We've been designing hard-to-use ballots since this country began, and that's not about to change," Jones quips. The latest worry is about tampering with DREs. Before polls open, workers insert a flash memory card into each machine to set the ballots. A virus impregnated in the cards could alter the recording of results, a scheme demonstrated by Edward W. Felten, a computer science professor at Princeton University. Only one allegation of tampering has been brought to court, however, and investigations showed that the odd voting pattern was because of bad ballot design.

Increasing spending on elections could improve security, accuracy and ballot design. But jurisdictions try to run elections on the cheap, Jones says, so machine makers operate on thin margins and there is little money for testing.

DID YOU KNOW ...

ABSENT: For most absentee ballots, voters fill in ovals on a page and mail it to their county election center. High-speed optical scanners that can count 10 ballots a second process the returns. The scanners reject problematic ballots, which are supposed to be adjudicated by a resolutions board but sometimes just get ignored, according to Douglas W. Jones of the University of Iowa. It is not uncommon for 4 to 10 percent of absentee ballots to go uncounted.

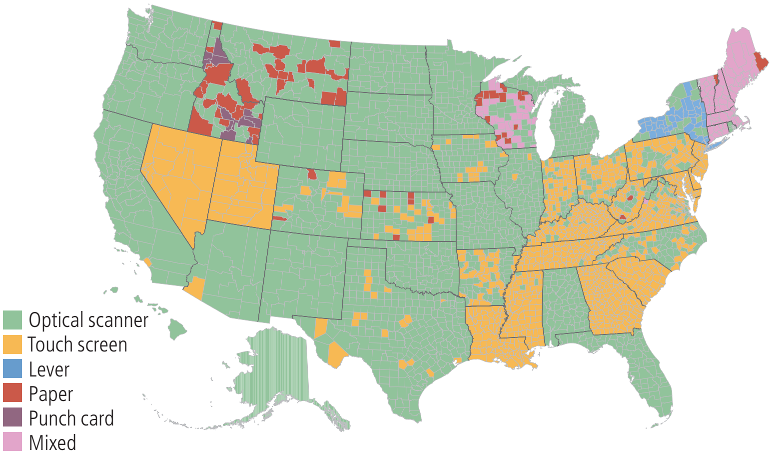
ONLINE: Internet voting is increasingly used for company shareholders' meetings, but it is rare in politics. Estonia, the Netherlands and Geneva, Switzerland, have tried it for general elections, and Okaloosa County, Florida, is promoting a pilot project for the race this November. But until security can be ensured—a tall order—most computer scientists say states should not commit.

LEVER MACHINE

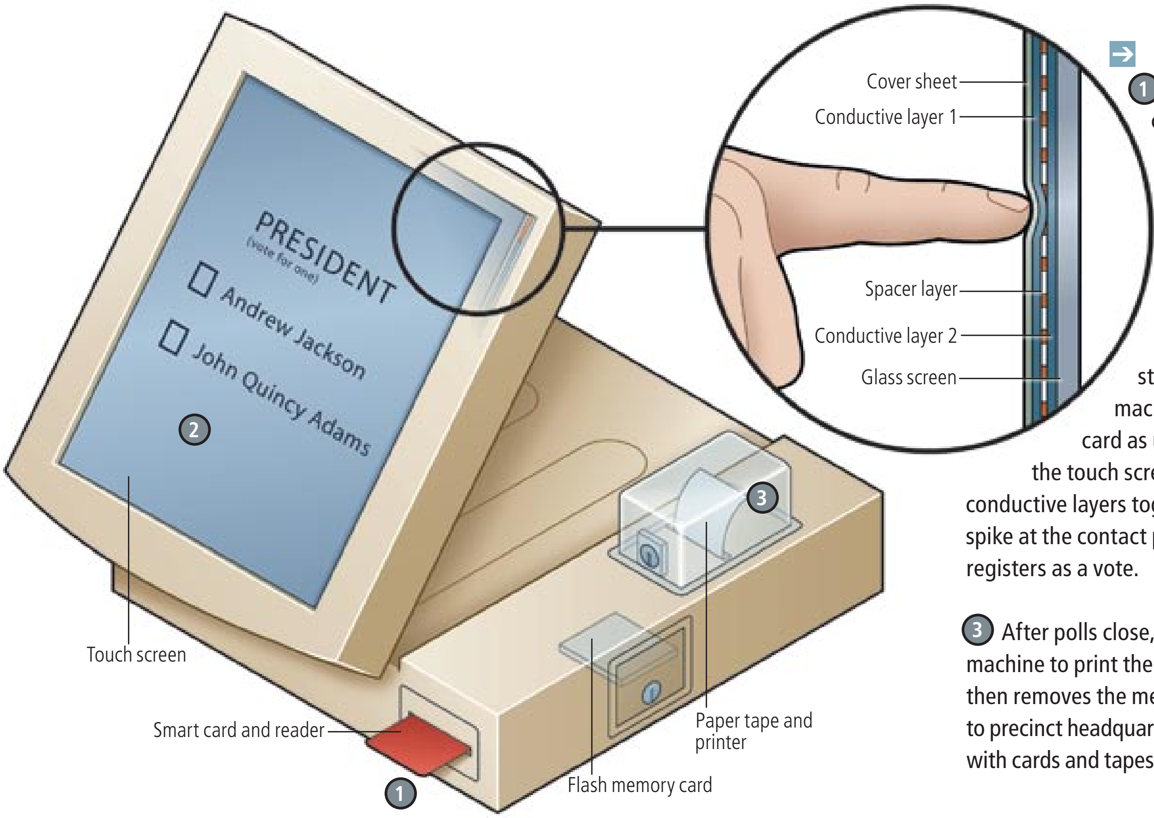
A voter closes a curtain, then turns a lever for each desired candidate. Pulling the arm that reopens the curtain causes counter wheels behind each turned lever to advance a notch (like an odometer) and resets the levers. When polls close, supervisors read the counters for totals.

VOTING TECHNOLOGY

Each county selects a technology. Optical scanners and touch screens prevail.



AP PHOTO (*voting booth*); SOURCE: ELECTION DATA SERVICES (*map*); TROY DOOLITTLE *TopDog Illustration* (*touch screen and optical scanner*)

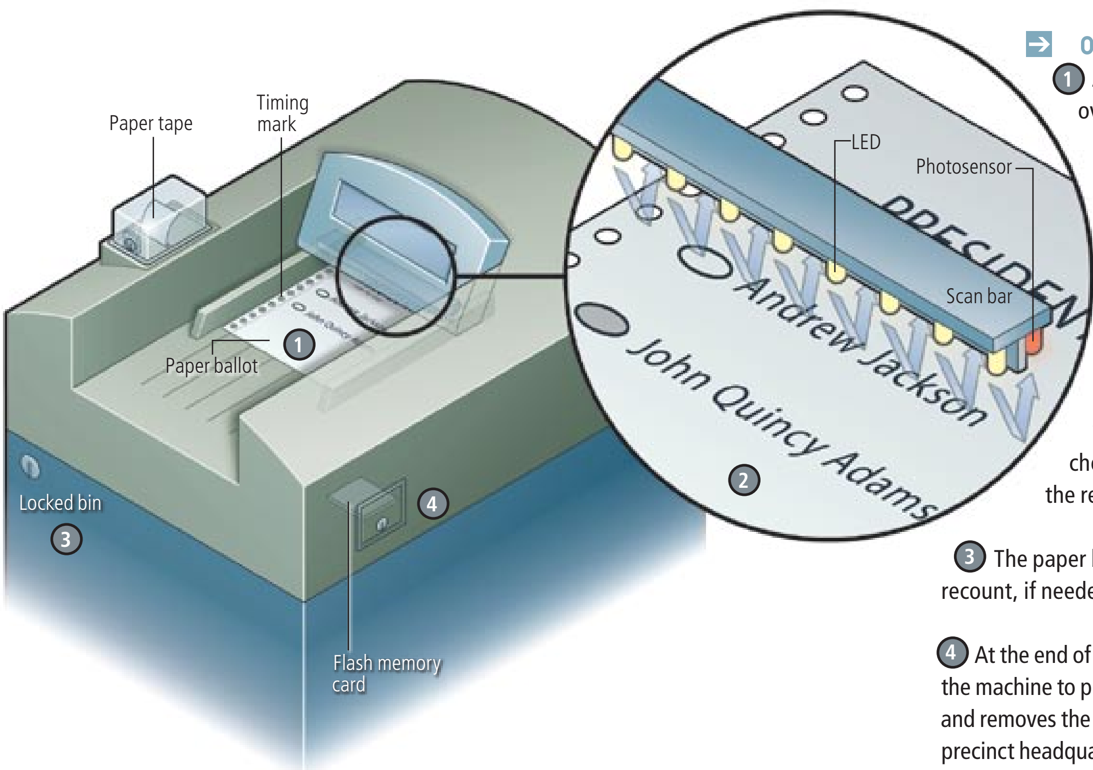


TOUCH SCREEN

1 A smart card or security code provided by poll workers is inserted, which allows a voter to complete one ballot.

2 The voter presses on-screen buttons to select candidates. A memory card stores the choices, and the machine then marks the smart card as used and ejects it. Pressing the touch screen (*inset*) pushes two thin conductive layers together, causing a voltage spike at the contact point, which software registers as a vote.

3 After polls close, a supervisor instructs the machine to print the vote totals on a paper tape, then removes the memory card. Both are brought to precinct headquarters, where they are tallied with cards and tapes from other machines.



OPTICAL SCANNER

1 A voter fills in targets, usually ovals, on a paper ballot, then feeds the page into a scanner.

2 A row of light-emitting diodes (LEDs) illuminates the paper as it scrolls by. An array of sensors picks up the reflections from timing marks on the ballot's edge indicating the office being elected and from the "dark spots" indicating the voter's choices. A memory card stores the result.

3 The paper ballot falls into a sealed bin for recount, if needed.

4 At the end of the day, a supervisor instructs the machine to print the vote totals on a paper tape and removes the memory card. Both are brought to precinct headquarters to be tallied with others.

SEND TOPIC IDEAS *to workingknowledge@SciAm.com*

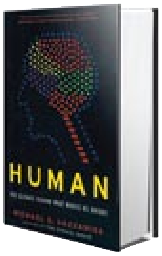
Barbara Juncosa contributed reporting for this article.

A Very Human Obsession ▪ Physics Out of Whack ▪ The World of the Small

BY MICHELLE PRESS

➡ HUMAN: THE SCIENCE BEHIND WHAT MAKES US UNIQUE

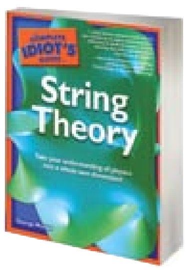
by Michael S. Gazzaniga. Ecco/HarperCollins, 2008 ($27.50)



"I always smile when I hear Garrison Keillor say, 'Be well, do good work, and keep in touch,'" Gazzaniga writes. In that one sentence, "Keillor captures humanness." In his own easy-to-read, conversational style, Gazzaniga, a neuroscientist at the University of California, Santa Barbara, and author of a slew of popular books, takes off in search of what set humans apart from their predecessors. His entertaining tour includes some of the most lucid explanations of scientific concepts around as well as discursions into art, aesthetics, empathy, ethics, cyborgs, animals on trial and what it would be like to date a chimp. Neuroscience has focused on the brain systems underlying possible decisive traits that are uniquely human—language, memory, emotion—but it has not usually considered the point Keillor intuitively conveys: most of the time humans are thinking about social relationships. We really do want to stay in touch.

➡ THE COMPLETE IDIOT'S GUIDE TO STRING THEORY

by George Musser. Alpha, 2008 ($16.95)



Okay, so you're not an idiot. You'll still like this guide to string theory. First, the easy-to-follow review of relativity, quantum mechanics, the Standard Model, the possibility of time travel, and much more. Then, the way alternatives to string theory play a role. And, crucially, the fluent understanding of the concepts, conveyed in everyday, even breezy, language. String theory, the leading proposal for unifying relativity and quantum theory, interprets subatomic particles as tiny vibrating strings. Tiny, Musser (who is an editor and writer at this magazine) emphasizes, is really tiny. The relation of a string to an atom is the same as that of a human to the entire visible universe.

The next few years will be critical for string theory. The Large Hadron Collider (LHC), "the world's most powerful and most expensive hammer," will begin to smash particles into bits to see what they are made of and to give new types a chance to form. But despite the promise of the LHC, unification, Musser warns, won't be a matter of solving equations and filling in details. Finishing the job will require new conceptual input.

EXCERPT

➡ THE BLACK HOLE WAR: MY BATTLE WITH STEPHEN HAWKING TO MAKE THE WORLD SAFE FOR QUANTUM MECHANICS

by Leonard Susskind. Little, Brown, 2008 ($27.99)

Susskind, a professor of theoretical physics at Stanford University, delivers a beautifully written account of the battle over the true nature of black holes that he and Dutch physicist Gerard 't Hooft have waged with Stephen Hawking:

"In 1976 Stephen Hawking imagined throwing a bit of information—a book, a computer, even an elementary particle—into a black hole. Black holes, Hawking believed, were the ultimate traps, and the bit of information would be irretrievably lost to the outside world. This apparently innocent observation was hardly as innocent as it sounds; it threatened to undermine and topple the entire edifice of modern physics. Something was terribly out of whack; the most basic law of nature—the conservation of information—was seriously at risk. To those who paid attention, either Hawking was wrong or the three-hundred-year-old center of physics wasn't holding....

"The Black Hole War was a genuine scientific controversy—nothing like the pseudo-debates over intelligent design, or the existence of global warming. Those phony arguments, cooked up by political manipulators to confuse a naive public, don't reflect any real scientific differences of opinion. By contrast, the split over black holes was very real.... It was not a war between angry enemies; indeed the main participants are all friends. But it was a fierce intellectual struggle of ideas between people who deeply respected each other but also profoundly disagreed."

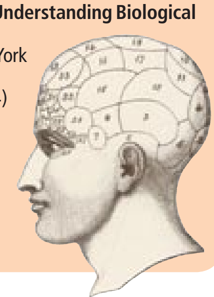
NEW AND NOTABLE: MINDS AND BRAINS

1. **Mirroring People: The New Science of How We Connect with Others**
by Marco Iacoboni. Farrar, Straus and Giroux, 2008 ($25)
A pioneer in the revolutionary research tells of the discovery of cells in our brain—called mirror neurons—that account for the remarkable ability to get inside another person's head.

2. **Loneliness: Human Nature and the Need for Social Connection**
by John T. Cacioppo and William Patrick. W. W. Norton, 2008 ($25.95)
Chronic loneliness disrupts perceptions, behavior, even physiology.

3. **Beautiful Minds: The Parallel Lives of Great Apes and Dolphins**
by Maddalena Bearzi and Craig B. Stanford. Harvard University Press, 2008 ($24.95)
Parallel evolution gave rise to the striking intelligence of these otherwise dissimilar animals.

4. **The Criminal Brain: Understanding Biological Theories of Crime**
by Nicole Rafter. New York University Press, 2008 ($72; paperbound, $24)
Reexamines a disturbing possibility: that a tendency toward criminality may be inherited as a set of genetic deficits.



MICHAEL OWEN AND JOHN BLONDIN *North Carolina State University (black hole)*; MARY EVANS PICTURE LIBRARY *(phrenological model)*

What would happen to Earth if the moon were only half as massive?

Neil F. Comins, author of *What If the Moon Didn't Exist?* and professor of physics and astronomy at the University of Maine, cuts this mystery down to size:

A less massive moon would be closer to Earth, for starters: the tidal forces that slowly widen the moon's orbit around Earth would be curtailed. There would be profound effects on our planet and its denizens as well.

The real moon orbits at an average distance of around 238,600 miles, but every year it drifts about 1.6 inches farther away. The cause? Ocean tides. The moon's gravity, combined with the waltz of Earth and the moon around a common center of mass, forces the oceans into an oval shape, with two simultaneous high tides. One high tide is on the side of Earth facing the moon; the other is on the opposite side of our world. Because Earth spins so rapidly compared with the moon's orbit, our planet drags the high tide closest to the moon a little bit ahead of it. The gravitational pull of the water imparts energy to the trailing moon, spiraling it a little farther outward with every orbit.

If the moon were half its mass, the tides would be correspondingly smaller and would impart less orbit-expanding energy to the moon. Even though a half-mass moon would require less energy to repel, the tides would be so weakened as to nonetheless bring about a closer moon.

The energy given to the moon comes from Earth's rotation, and our planet is slowing down as a result—in other words, days are getting longer. Geologists believe that an Earth day was originally five or six hours long. If the moon were less massive, thereby creating less drag on Earth, our planet would not have slowed as much. The day would be perhaps 15 hours long.

Weaker tides also would not have eroded Earth's landmasses so drastically over the past few billion years. Less soil leaching into the ocean might have had profound effects on the origin of life: some organic (carbon-based) compounds thought to have seeded life may not have reached the primordial soup of the early oceans.

Assuming that life had still arisen, it would have had to contend with more frequent ice ages and more extreme warm snaps, because large moons act to stabilize planets. Mars, whose two tiny moons combined are millions of times less massive than our full-size moon, wobbles dramatically on its axis and so endures bigger climatic swings and seasonal temperature changes than Earth does.

The outlook for life would have been dim—literally. A smaller moon means less moonlight, which means darker nighttimes. Whatever life-forms did evolve on this altered Earth would have had to develop bigger or more sensitive eyes to help them navigate, forage and spawn at night under the diminished glow.

Why don't we get more drinking water from desalinating the ocean?

Peter H. Gleick, president of the Pacific Institute, a nonprofit environmental and water policy think tank based in Oakland, Calif., distills an answer:

The desalination of water requires a lot of energy and, hence, money. The price varies widely from place to place, ranging from just under a dollar up to several dollars to produce a cubic meter (264 gallons) of desalted water, and efforts to reduce the energy requirements have not kept pace with rising energy costs. The cost of drawing freshwater from a river or aquifer is much lower—about 10 to 20 cents per cubic meter—and farmers often pay even less. As a result, desalination currently satisfies less than half a percent of human water needs.

Desalination carries environmental costs as well: seawater intakes can suck up small ocean creatures, upsetting the food chain, and the process's leftover brine is so strong that its return to the ocean can prove harmful to coastal ecosystems.

Nevertheless, desalination's appeal is growing as other sources of water disappear and the price gap closes. Finding a new source of freshwater or building a dam in a place such as California, for instance, can drive costs up to 60 cents per cubic meter. Far more must be done to use water more efficiently, but with the world's population swelling and the water supply dwindling, the economic tide may soon turn in favor of desalination. ■

DESALINATION INTAKE, PERU

HAVE A QUESTION?... *Send it to experts@SciAm.com or go to* **www.SciAm.com/asktheexperts**

NASA (*moon*); MARIANA BAZO *Reuters* (*pipes and ocean*)