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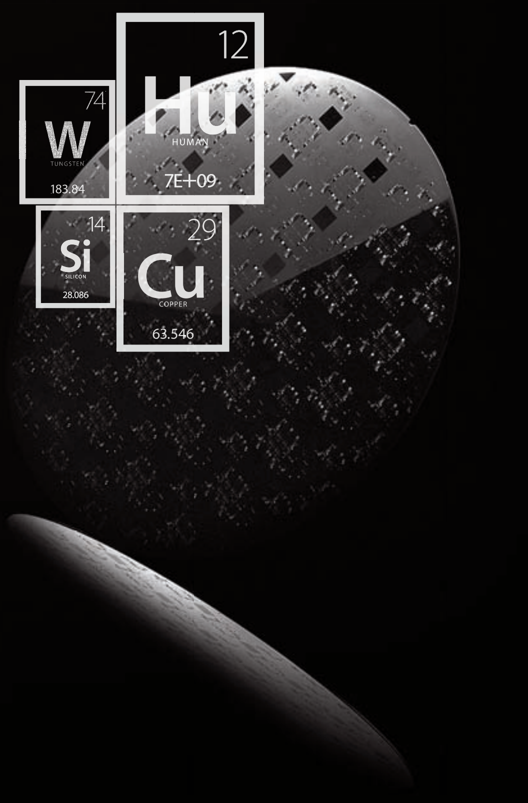
I am the Human Element in the relentless pursuit of making things faster and smaller. Electronic materials, chips and semiconductor technology, these are the things I live and breathe every day. Innovation in this world happens at the molecular level. And success is in the power of small.

~Dr. George Barclay
Dow Electronic Materials



ON THE COVER

During a long-ago climate catastrophe a small group of *Homo sapiens* found refuge in a bountiful seashore near Africa's tip. We are all the beneficiaries. IMAGE BY JEAN-FRANCOIS PODEVIN.

PER-ANDERS PETTERSON (*cover background*); FRANK HÜLSBÖMER (*robot pill*)

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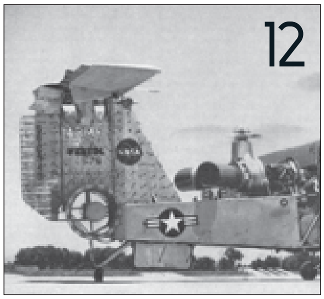

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COURTESY OF THE LINDAU NOBEL LAUREATE MEETINGS; COURTESY OF ANYBOTS *(robot)*

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Celebrating Science

In 1845 James K. Polk succeeded John Tyler, Jr., as the 11th president. The U.S. annexed Texas as the 28th state, and the young nation's "manifest destiny" to occupy all of North America became a popular ideal. The industrial revolution was burgeoning, easing people's lives with mechanical marvels. By this time, for instance, Cyrus McCormick had created a labor-saving reaper for crops. And with a promise to explain "New Inventions, Scientific Principles, and Curious Works," the painter and inventor Rufus Porter introduced the first issue of a broadsheet called *The Scientific American* on August 28, 1845.

Porter was "a mechanical Johnny Appleseed sowing seed of new and ingenious ideas as he traveled through New England and abroad through his journals," wrote Jean Lipman in *Rufus Porter, Yankee Pioneer* (Clarkson N. Potter, 1968); you can learn more about him at the Rufus Porter Museum in Bridgton, Me. Porter took out more than 100 patents, but his best-known innovation is his revolver mechanism, which he sold in 1844 to Samuel Colt for $100. *Scientific American* reflected his broad interests. The inaugural edition lists patents, describes developments such as Samuel Morse's telegraph and a filter for locomotive smoke, comments on painting portraits and even includes poetry. Find excerpts in a special 50, 100 and 150 Years Ago, starting on page 12; other excerpts from the 1845 issue and a slide show appear at www.ScientificAmerican.com.

True to Porter's restless nature, he sold the publication after only 10 months to Orson Desaix Munn and Alfred Ely Beach, both in their early 20s. Beach was also an inventor—he designed New York City's first subway, the Beach Pneumatic Transit (an 1870 issue featured the plans). *Scientific American* is included in an exhibit at the Newseum in Washington, D.C., on the history of journalism in the 1800s. Munn & Co. had a successful patent agency that shepherded more than 1,000 applications, and it ultimately held *Scientific American* for more than a century.

When Charles Darwin published *On the Origin of Species, Scientific American* covered it. Thomas Edison came into the office and demonstrated his work for the staff. With editorials and silver trophies to reward flights of increasing distances, the editors goaded the Wright brothers to reveal details of their flying machines. Albert Einstein once penned an article for our pages. The magazine saw the U.S. through its Sputnik moment and the start of the "space age."

This is *Scientific American*'s 165-year heritage as the country's oldest continuously published magazine. Yet in every issue, the magazine is new again, with its scientist authors, many of them Nobel Prize winners, and top journalists describing the latest in science and technology. In this edition, feature articles cover everything from threats to the computers we now rely on ("The Hacker in Your Hardware," page 82) to devices that will make "fantastic voyages" in medicine a reality ("Robot Pills," page 62) to extrasolar Earth-like planets that might harbor life ("Planets We Could Call Home," page 38). Fittingly, we include a special report on "Origins" (page 46).

So Happy Birthday to *Scientific American* this month. We hope you will join us in celebrating the renewal and positive force of science in our world every day. ■

Mariette DiChristina
editor in chief

ETHAN HILL (*DiChristina*); *SCIENTIFIC AMERICAN*, VOL. 1, NO. 1; AUGUST 28, 1845 (*logo*)

Letters to the Editor

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Letters may be edited for length and clarity. We regret that we cannot answer each one. Post a comment on any article at
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LETTERS editors@SciAm.com

Growth ▪ More Growth ▪ Faulty Circuits

APRIL 2010

"Isn't growth for the sake of growth the philosophy of cancer?"
—*John Langerak* CHESTER, ME.

■ Planning for Earth

Peter H. Gleick's "Freshwater Use" [Solutions to Environmental Threats] neglected to mention one obvious water-conservation measure: meter all freshwater and charge for it. Why should some—most notably agribusiness—receive this valuable resource for free? It is already the policy in some countries to assume that all freshwater is the property of the federal government, owned by all citizens equally. If we were to adopt such a policy in the U.S., we could use the money so collected to install free low-flow toilets, showerheads, and so on in all public housing. It could also be used to partially underwrite farmers converting to drip irrigation and soil-moisture sensors, perhaps in exchange for a promise not to raise food prices as a result of increased irrigation costs. Making everyone pay for what they actually use is always good policy: the profit motive encourages conservation.

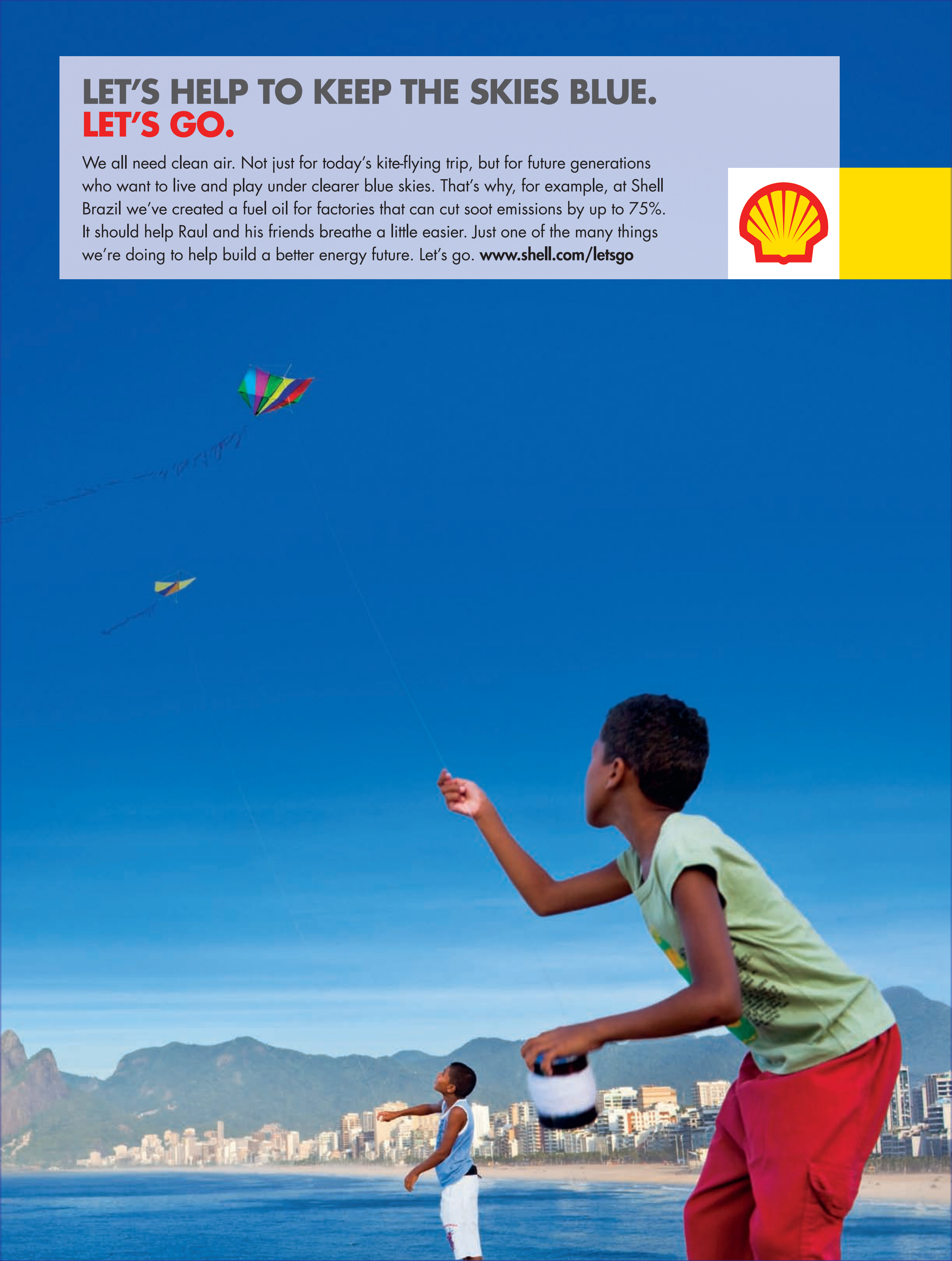
Robert Russell
Chapel Hill, N.C.

I am both saddened and dismayed that, once again, you devote the better part of an issue to the problems of sustainability while barely mentioning the root cause of most of the threats to our world: population growth. While I concur with the steps you outline to address biodiversity loss, ocean acidification, climate change, and the like, these are but symptoms of the underlying problem. Ultimately, no technological solution can succeed without tackling the issue of demand. As long as the world's population continues to grow, the incessant pressure for more land, more food and more energy will continue, dwarfing any gains to be had through conservation and technology. Modern medicine and modern fertilizers have triggered the population explosion of the past 200 years, but the human drive to procreate hasn't adjusted to the realities of the modern world. We as a species must voluntarily act to reduce our population to sustainable levels, or else Mother Nature will almost certainly do it for us through war, famine and disease. Increased funding for family planning, tax laws that discourage multiple children, and a shift away from a growth-based economy (which depends in part on an increasing population) must be part of any plan for a sustainable future.

Danny Rosenberg
Portland, Ore.

Jonathan Foley's otherwise excellent "Boundaries for a Healthy Planet" falls short, in my view, in one very important respect. In his introduction he mentions the growth of population and of consumption, saying this has expanded to a global assault and observing that we live in a full world. Yet the rest of the article is confined to discussing ways of limiting the consequences of this growth, without any consideration of limiting growth itself. But should not population itself be subject to a threshold?

The world's population continues to


LET'S HELP TO KEEP THE SKIES BLUE.
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We all need clean air. Not just for today's kite-flying trip, but for future generations who want to live and play under clearer blue skies. That's why, for example, at Shell Brazil we've created a fuel oil for factories that can cut soot emissions by up to 75%. It should help Raul and his friends breathe a little easier. Just one of the many things we're doing to help build a better energy future. Let's go. www.shell.com/letsgo

grow at more than 360,000 a day. The most often quoted figure of nine billion in 2050 is generally quoted uncritically, but this figure, now updated to 9.2 billion, is only the middle of three projections by the United Nations Population Fund; the actual figure could be as high as 10.5 billion. This will affect for the worse all the other environmental processes identified in the article, especially freshwater, land use and biodiversity.

A recent article in a special issue of *Scientific American* ["Population & Sustainability," by Robert Engelman; Scientific American Earth 3.0, June 2009] pointed out that the number of unintended pregnancies is almost the same as the number by which population increases, so it should be possible to address the problem of population increase in a wholly noncoercive way. Moreover, according to the U.N. Population Fund, 200 million women would use family planning but have no access to it. As a result, according to the World Health Organization, 20 million women undergo unsafe abortions with a horrifying death toll as a consequence. Therefore, there is clearly a huge unfulfilled demand for family planning.

Roger Plenty
Stroud, U.K.

DRIP IRRIGATION is one water-saving technique that could help make agriculture sustainable in an increasingly dry world.

BOB ROWAN *Progressive Image/Corbis*

Kicking the Habit

I did not think I would live long enough to read an article dealing with the subject matter in "Breaking the Growth Habit," by Bill McKibben. During my 72 years as a citizen of the U.S., I've lived out West, back East, up North and down South. There was always a local chamber of commerce stating that if a town was not in a perpetual state of growth, it was not healthy. Isn't growth for the sake of growth the philosophy of cancer?

John Langerak
Chester, Me.

Much of what McKibben writes is silly. The idea of completely stopping economic growth is not only crazy but in one fell swoop dooms the couple of billion people living below the poverty level on Earth, as well as their descendants, to bare subsistence living for eternity. That is not only nuts, it is morally indefensible. His ideas on local agriculture are also way off track.

I happen to have lived in a rural community before "industrial farming" existed. I remember the lean diet we had during winter: root vegetables, cabbage as the only salad, canned beans and tomatoes, etcetera, but no fresh green vegetables at all. I do not want to go back to that, nor do I need to. I like having fresh Chilean blueberries available in midwinter, crisp lettuce all year long as well as a cornucopia of other fresh, healthy produce. If McKibben wants to revert back to the lean old days, fine—but do not preach it to me!

Richard L. Huber
New York City

Cartesian Duality

As an investigator, I appreciate how Thomas R. Insel's "Faulty Circuits" ends with a few comments regarding the transition taking place in psychiatry from a subjective, mental-based discipline to one thoroughly grounded in neuroscience. The intrinsic Cartesian dualist bias that has for so long restrained psychiatry may at long last be loosening its grasp, thus allowing psychiatry to join the other medical specialties, thoroughly grounded in sound scientific practice.

Bob Schwartz
Chester, Vt.

ERRATUM In Edward Bell's "8 Wonders of the Solar System," a caption described the Herschel crater on Saturn's moon Mimas as a 13-kilometer-wide depression. The crater's actual width is 139 kilometers.

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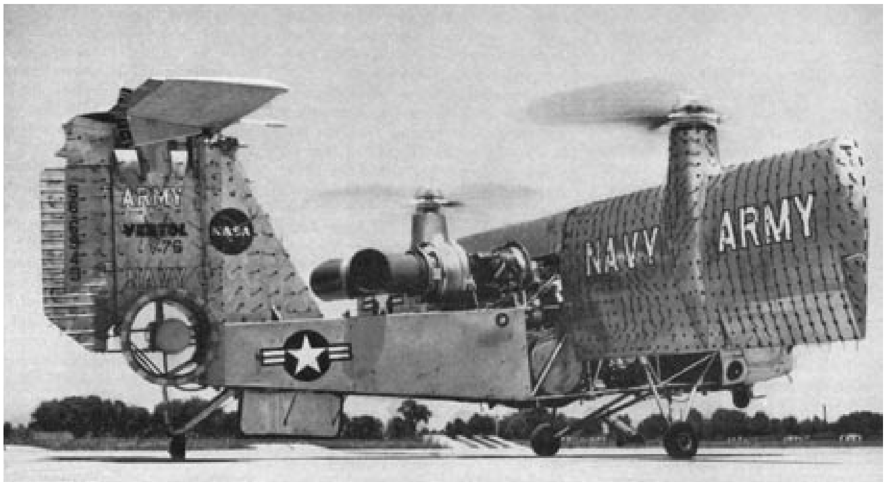
Vertical Takeoff ▪ Evolution Debate ▪ *Scientific American* Is Born

Compiled by Daniel C. Schlenoff

AUGUST 1960

STRAIGHT UP—"Active research on vertical takeoff and landing (VTOL) aircraft is in progress both here and abroad. In this country the program has been a three-way collaboration among the National Aeronautics and Space Administration, a number of aircraft manufacturers and the armed forces. The requirements of commercial passenger traffic are not the only, nor even the major, impetus behind the investigations. The Army, Navy and Air Force are interested in a variety of aircraft that could operate in forward areas without the need for prepared landing strips. Interceptor, reconnaissance and cargo types are all being studied. So far as freight carrying aircraft are concerned, they would obviously have both commercial and military applications."



VERTICAL TAKEOFF AIRCRAFT: A nascent technology with rotating wings, 1960. Strips of cloth on the wing surfaces of this Vertol-76 aircraft are "telltales" used to track airflow.

AUGUST 1910

FORESTS AND FLOODS—"A lively war of words has raged of late, in both Europe and America, over the question of the influence of forests upon stream-flow. In reading the literature of this intricate problem, one is impressed that a great deal of theorizing has been done upon a slender basis of facts. The recognition of this fact has led the United States Weather Bureau and the United States Forest Service to undertake jointly a series of investigations designed to supply precisely the data needed. A complete study of the effects of forest cover upon stream-flow, erosion, disposition of silt, etc., will be carried out on two watersheds of similar topography near Wagon Wheel Gap, Colorado. It is intended to measure the flow of the two streams for a period of eight or ten years; one of the watersheds will then be cleared, and the measurement continued for a further period of eight or ten years, so that the effects of denudation may be perfectly determined." [NOTE: The Wagon Wheel Gap project was the first controlled experiment in the U.S. on the influence of forests on stream-flow. Cutting forests did increase stream-flow, but after seven years, new vegetation largely reduced it again.]

LIGHT COINS—"The French Government has decided not to adopt aluminium coinage. A number of aluminium coins were made as a test, but the lightness of the white metal, which was one of its chief recommendations, has condemned it. A five-centime piece (one cent) made of aluminium weighed only 1.9 grams, as against 5 grams in bronze, and it is thought that a coin so light would slip through the fingers, especially the rough fingers of a workman."

AUGUST 1860

MINOT'S LEDGE LIGHTHOUSE—"The new lighthouse off Massachusetts is expected to be completely finished and lighted up on the first week of next month. The first blow struck upon the rock where this lighthouse has been erected was on the 12th June 1858. The old iron lighthouse was carried away by the fearful storm of April 1851 [*along with the two assistant keepers who had remained at their posts*]. During the numerous and severe storms of last winter, the new lighthouse stood exposed to the merciless pelting of the waves of the wild Atlantic, without a stone or joint having been disturbed. Having stood without damage in this naked and exposed condition, nothing can prevail against it when finished." [NOTE: The lighthouse still stands and was fully automated in 1947.]

DARWIN MAKES WAVES—"At the British Association for the Advancement of Science meeting, the paper which has perhaps called forth the greatest amount of keen and excited discussion was that of Professor Draper, of this city, on the intellectual development of Europe, considered with reference to the views lately propagated by Dr. Darwin.

Dr. Draper showed that the advances of men are due to external and not to interior influences, and that in this respect a nation is like a seed, which can only develop when the conditions are favorable; that all organisms and even man are dependent for their characteristics, continuance and life, on the physical conditions under which they live; that the existing apparent invariability presented by the world is the direct

SCIENTIFIC AMERICAN, VOL. 203, NO. 2; AUGUST 1960

consequence of the physical equilibrium, but that if that should suffer modification, in an instant the fanciful doctrine of the immutability of species would be brought to its proper value."

DARWIN BACKLASH—"The above paper attracted an immense audience.

Sir Benjamin Brodie stated that he could not subscribe to the hypothesis of Dr. Darwin. Man has a power of self-consciousness as a principle differing from anything found in the material world. This power of man was identical with the divine intelligence; and to suppose that this could originate with matter involved the absurdity of supposing the source of divine power dependent on the arrangement of matter.

The learned and venerable Bishop of Oxford stated that the Darwinian theory, when tried by the principles of inductive science, broke down. The permanence of specific form was a fact confirmed by all observation. The remains of animals, plants and man found in those earliest records of the human race—the Egyptian catacombs—all spoke of their identity with existing forms, and of the irresistible tendency of organized beings to assume an unalterable character.

Dr. Hooker, the celebrated botanist, having been called upon for his views, said that they accorded with those of Mr. Darwin, and that the Bishop of Oxford did not understand them.

Mr. Darwin seems to have set the scientific world by the ears; it is no easy thing to arrive at what he does mean."

STILL RELIABLE—"I have been taking your paper for ten years; its chief excellence, in my opinion, is its perfect *reliability* and the total absence of *clap-trap* and *humbug*. I do not believe that you can be bribed to say of somebody's fly-trap that it will catch more flies and bigger flies than anybody else's fly-trap."

SCIENTIFIC AMERICAN, VOL. 1, NO. 1; AUGUST 28, 1845

165 YEARS AGO: HAPPY BIRTHDAY TO US

AUGUST 1845

"New-York, Thursday, August 28, 1845" was the cover date for the first issue of *Scientific American: The Advocate of Industry and Enterprise, and Journal of Mechanical and Other Improvements*. For $2 a year, readers were promised a weekly broadsheet that would cover "*New Inventions, Scientific Principles, and Curious Works.*" Now, 165 years later, we have gone through as many transitions as the fields we cover, but we continue to do our best to deliver coverage on new inventions, the frontier of scientific theory and, occasionally, curious works. Here is a sampling from that issue:

MORSE'S TELEGRAPH—"This wonder of the age, which has for several months past been in operation between Washington and Baltimore, appears likely to come into general use through the length and breadth of our land. It is contemplated by the merchants of our Western states, to communicate their orders for goods, &c. by means of the telegraph, instead of abiding the slow and tedious progress of railroad cars."

AGE OF STEAM—"The Steam-Ship *Great Britain,* the mammoth of the ocean, which has recently arrived from Liverpool, has created much excitement here as well as in Europe; being in fact the greatest maritime curiosity ever seen in our harbor. She was built by the Great Western Steam-Ship Company, at Bristol, England. She is composed entirely of iron. During the few days since her arrival at New York, she has been visited by about 12,000 people who have paid 25 cents for the gratification. If there is any thing objectionable in the construction or machinery of this noble ship, it is the mode of propelling her by the screw propeller; and we should not be surprised if it should be, ere long, superceded by paddle wheels at the sides."

FULL STEAM AHEAD: The *Great Britain,* Isambard Kingdom Brunel's first mammoth steamship, in an engraving from our first issue, 1845.

See a slide show of some highlights of our history, including our first issue, at **www.ScientificAmerican.com/sciammag/aug2010**

NEWS SCAN

INSIGHTS AND ANALYSIS ABOUT SCIENCE AND TECHNOLOGY

ENERGY & ENVIRONMENT

Biological Breakdown

The job of cleaning up after the Gulf oil spill will fall to the microbes BY DAVID BIELLO

SKIMMERS, SCOOPS and thousands of kilometers of booms cannot compare with bacteria and other microbes when it comes to removing oil. The microorganisms that naturally inhabit the Gulf of Mexico are the only real defense against the Deepwater Horizon spill. As researchers study how the microbes are cleaning up the mess, they remain wary of how these saviors could also choke marine life, too.

That natural microbes are better than human mop-up efforts may come as a surprise, considering that for decades, genetic engineers have touted the creation of an oil-gobbling superbug—the first patent issued for a genetically modified organism was for such a hydrocarbon-chewing microbe. But such microbes "are not effective for the most part," says marine microbiologist Jay Grimes of the University of Southern Mississippi.

Engineered microbes come up short in part because no single organism, no matter how much it is enhanced, can beat the strength of a community of individual organisms, each with its own hydrocarbon-consuming specialty. In "every ocean we look at, from the Antarctic to the Arctic, there are oil-degrading bacteria," says microbiologist Ronald M. Atlas of the University of Louisville, who evaluated genetically engineered microbes and other cleanup ideas in the wake of the *Exxon Valdez* spill. "Petroleum has thousands of compounds. It's complex, and the communities that feed on it are complex. A superbug fails because it competes with this community that is adapted to the environment."

If you can't beat them, why not join them? Encouraging these bugs to work harder is theoretically possible through the use of fertilizers, such as iron, nitrogen and phosphorus. In fact, such an approach accelerated microbial activity in the sediment along the Alaska coast after the *Valdez* disaster. "We saw a three to five times increase in rate of biodegradation," Atlas recalls.

The technique, however, is not likely to pay off in the Gulf. "In the ocean, how do you keep the nutrients with the oil?" asks microbial ecologist Kenneth Lee, director of the Center for Offshore Oil, Gas and Energy Research with Fisheries and Oceans Canada. He notes that "you don't see bioremediation in the open ocean." Even fertilizing onshore could prove problematic. Lee tried tilling oil-soaked wetlands in Nova Scotia where there was limited oxygen to increase microbial activity. "That didn't work. We had large erosion as a result," he says.

Chemical dispersants, which break up the slick, are perhaps the only way to boost microbial activity in the Gulf. "If the oil is in very small droplets, microbial degradation is much quicker," says Lee, who has been measuring oil droplets to determine the effectiveness of dispersants.

Microbial consumption of oil, however, works best near the

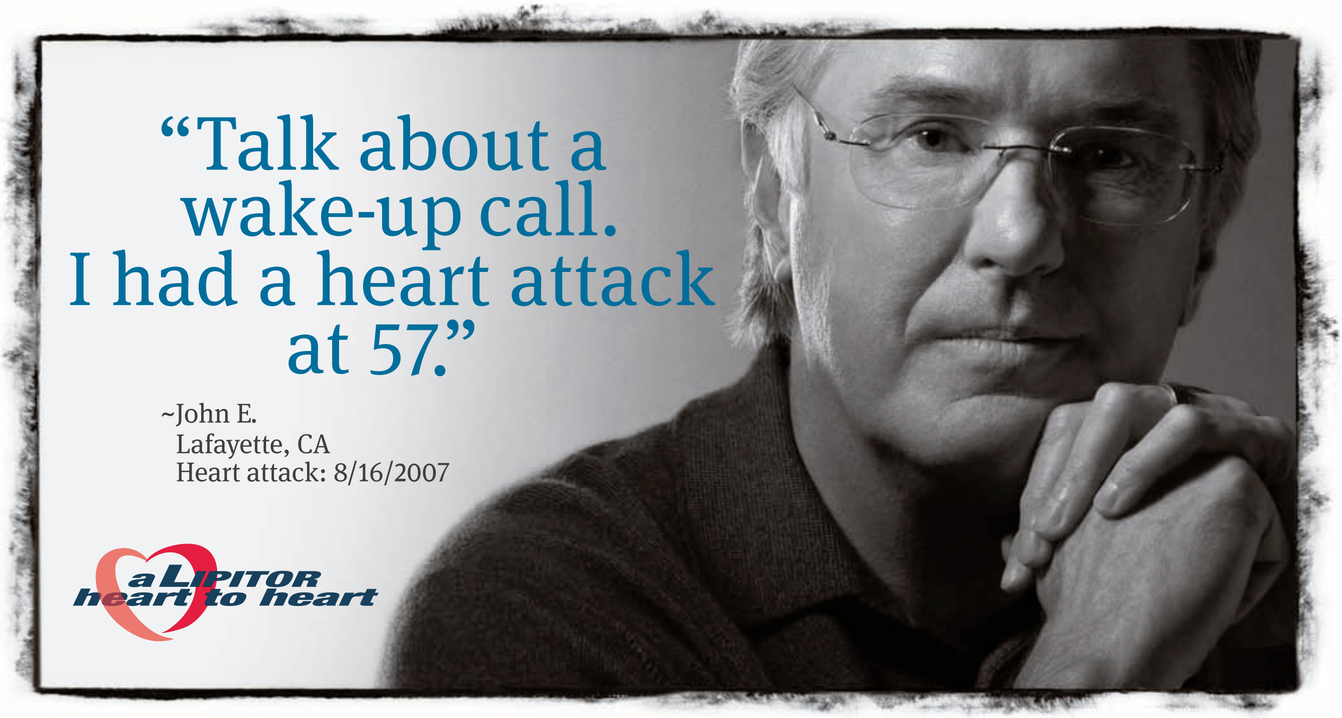
CRUDE CONDITIONS: The Gulf spill has reached the U.S. coastline, including here at the mouth of the Mississippi River in Louisiana. Microbes will break down the oil, but possibly not for decades.

CHARLIE RIEDEL *AP Photo*

warm surface waters. "Metabolism slows by about a factor of two or three for every 10 degrees Celsius you drop in temperature," notes biogeochemist David Valentine of the University of California, Santa Barbara, who is studying the microbial response to the oil spill. Breakdown of oil in deep waters, he remarks, "is going to happen very slowly because the temperature is so low."

Unfortunately, that's exactly where some of the Deepwater Horizon crude seems to be ending up. Researchers "saw the oil at 800 to 1,400 meters depth," says microbial ecologist Andreas P. Teske of the University of North Carolina at Chapel Hill. His graduate student Luke McKay was on the research vessel *Pelican,* which first reported such subsurface plumes. Microbial activity is the only process to break down oil at depth. (At the surface, physical processes such as evaporation and waves help to eliminate oil from water.)

Microbes chomping on a spill the size of the Deepwater Horizon catastrophe come with a dark side. While eating the oil, the microbes consume the oxygen in the water, potentially asphyxiating aerobic organisms. Measurements of oxygen depletion weeks after the spill detected as much as a 30 percent drop in the Gulf of Mexico seawater. Although this amount of depletion has little impact on mobile marine life, scientists worry about anoxic



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If you take LIPITOR, tell your doctor if you feel any new muscle pain or weakness. This could be a sign of rare but serious muscle side effects. Tell your doctor about all medications you take. This may help avoid serious drug interactions. Your doctor should do blood tests to check your liver function before and during treatment and may adjust your dose.

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- **Muscle problems** that can lead to kidney problems, including kidney failure. Your chance for muscle problems is higher if you take certain other medicines with LIPITOR.
- **Liver problems**. Your doctor may do blood tests to check your liver before you start LIPITOR and while you are taking it.

Call your doctor right away if you have:

- Unexplained muscle weakness or pain, especially if you have a fever or feel very tired
- Allergic reactions including swelling of the face, lips, tongue, and/or throat that may cause difficulty in breathing or swallowing which may require treatment right away
- Nausea, vomiting, or stomach pain
- Brown or dark-colored urine
- Feeling more tired than usual
- Your skin and the whites of your eyes turn yellow
- Allergic skin reactions

Common side effects of LIPITOR are:

- Diarrhea
- Upset stomach
- Muscle and joint pain
- Changes in some blood tests

HOW TO TAKE LIPITOR

Do:

- Take LIPITOR as prescribed by your doctor.
- Try to eat heart-healthy foods while you take LIPITOR.
- Take LIPITOR at any time of day, with or without food.
- If you miss a dose, take it as soon as you remember. But if it has been more than 12 hours since your missed dose, wait. Take the next dose at your regular time.

Don't:

- Do not change or stop your dose before talking to your doctor.
- Do not start new medicines before talking to your doctor.
- Do not give your LIPITOR to other people. It may harm them even if your problems are the same.
- Do not break the tablet.

NEED MORE INFORMATION?

- Ask your doctor or health care provider.
- Talk to your pharmacist.
- Go to **www.lipitor.com** or call **1-888-LIPITOR**.

Uninsured? Need help paying for Pfizer medicines? Pfizer has programs that can help. Call **1-866-706-2400** or visit **www.PfizerHelpfulAnswers.com.**

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Rx only

effects down deep, where mixing with oxygen-rich surface waters is minimal. That spells bad news for the speedy breakdown of oil as well as for coral and other sessile deepwater life. Already dead sea cucumbers from the seafloor have bobbed to the surface, which could be a sign of a developing dead zone as much as an indication of oil toxicity itself.

Understanding how the microbes will work and how long they will take will require a better understanding of the amount of crude out there. Such predictions are "a function of size, and we don't know size," says microbial geochemist Samantha B. Joye of the University of Georgia. "We can't begin to make any kind of calculation of potential oxygen demand or anything else." Over time, that estimated amount has grown from an initial 1,000 barrels of oil per day to as much as 60,000 per day as of mid-June.

Whatever the case, that oil will linger in the environment for a long time. The microbes break down hydrocarbons in "weeks to months to years," Atlas explains. Nature provides a solution, albeit a slow one.

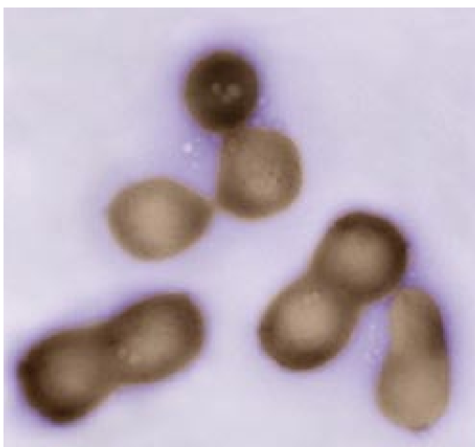
RESEARCH & DISCOVERY

Tools for Life

The ability to make cells with artificial genomes bodes well for basic biology BY DAVID BIELLO AND KATHERINE HARMON

THE FIRST MICROBE to live entirely by artificial genetic instructions began proliferating in a test tube in late March at the J. Craig Venter Institute in Rockville, Md. Venter and his colleagues built a synthetic genome for a strain of the *Mycoplasma mycoides* bacterium. The feat made headlines because it marked a major step in the creation of life in the laboratory. But it also demonstrated a refinement of the tools of genetic engineering that, the researchers hope, will eventually offer new insight into basic genetic processes and revolutionize biotechnology and drug development.

To make a working genome, Venter and his team stitched together various short iterations of man-made versions of nuclei bases (adenine, cytosine, guanine and thymine). They then inserted the final synthetic genome—a bit more than one million base pairs long but still simpler than the *M. mycoides*'s natural genome—into an existing *M. capricolum* cell. It booted up the natural cell's machinery and busily set to work making proteins and, ultimately, dividing and thriving. Within three days the researchers found a blue colony of *M. capricolum* living as synthetically driven *M. mycoides*. "This is the first self-replicating cell on the planet to have a computer for a parent," Venter quipped during a press briefing on May 20, the day the research was published online by *Science*.



MAN-MADE: **This electron micrograph shows the bacterial cells *Mycoplasma mycoides* that are the first to live with a genome synthesized in the lab.**

COURTESY OF TOM DEERINCK AND MARK ELLISMAN *National Center for Microscopy and Imaging Research, University of California, San Diego*

Getting to this point took at least $40 million in investment into relevant experiments during the past 15 years, which were primarily funded by Venter's private company Synthetic Genomics and the U.S. Department of Energy. The researchers also had to overcome several other challenges, including one that needed three months of cross-checking to find a single missing base that prevented life. "Accuracy is essential," Venter said. "There are parts of the genome where it cannot tolerate even a single error."

The genome also included four "watermarks" to distinguish the synthetic microbe—dubbed *M. mycoides* JCVI-syn1.0—from natural organisms. The watermarks are distinct genetic codes that include quotes: "To live, to err, to fall, to triumph, and to recreate life out of life," from James Joyce; "see things not as they are but as they might be," from J. Robert Oppenheimer; and "what I cannot build, I cannot understand," from Richard Feynmann. (In less than two weeks since the announcement of the achievement, 26 scientists had cracked the watermark codes, according to Venter.)

Synthetic biologists have lauded the work. "It is a big deal," says George M. Church, a geneticist and technology developer at Harvard Medical School. "It's not incremental, but it's not final either," he adds. Biological engineer Drew Endy of Stanford University thinks of the creation this way: "It's not genesis—it's not as if mice are coming from a pile of dirty rags in a corner," he says. "The correct word is poesis, human construction. We can now go from information and get a reproducing organism. It lays down the gauntlet for us to learn how to engineer genomes."

Going forward, Venter hopes to hone the techniques to begin synthesizing new vaccines for viruses as well as to be able to make them in days, rather than weeks or months. One of the group's long-term goals, Venter said at a June 1 Cold Spring Harbor Laboratory symposium, is to develop a universal recipient cell, into which researchers can plug a variety of synthetic genomes and see how they run. And someday, he surmised, it might be cheaper for scientists to synthesize simple organisms than to grow them.

The creation of an artificial genome, however, still has not demystified the origin of life. Investigators built much of the bacterium's genome without fully understanding the function of many of the million-plus base pairs involved.

But not unlike the way complex erector sets can elucidate some of the basic rules of physics and engineering, constructing—and deconstructing and reconstructing—whole genomes might help clarify genomic principles. Scientists, for instance, do not yet know what role or importance the order of genes in the genome plays. In some cases, genes can have their order swapped with little visible outcome on life, whereas a specific sequence might be more important elsewhere on the genome.

To decipher such basic genetic puzzles, one of Venter's co-author, Daniel G. Gibson, an institute molecular biologist, says that the researchers will also attempt to create the simplest genome possible that can still permit life. "This will help us to understand the function of every gene in a cell and what DNA is required to sustain life in its simplest form," he explains. He guesses this genome will be half as big as the bacterial genome they created.

As for those first synthetic cells, their time in the spotlight has ended for the moment. Currently they lie dormant in a Venter Institute freezer.

Danger in School Labs

Several headline-grabbing accidents have shone light on chronically poor safety records BY BERYL LIEFF BENDERLY

THE DAY SHEHARBANO "Sheri" Sangji, a 23-year-old technician at the University of California, Los Angeles, undertook what would be her last task, she wore a sweatshirt and no lab coat. That late December afternoon in 2008, she started working with a liquid called t-butyl lithium. The chemical requires careful handling, because as a pyrophoric, it catches fire when exposed to air. But equipment malfunctioned, and the fluid spilled, setting the synthetic fibers of her clothing ablaze. Two postdocs ran to help douse the fire engulfing Sangji, but they failed to get her to the nearby shower. Emergency personnel raced to the scene, but they arrived too late. She spent 18 days in a hospital burn unit before she died.

Sangji's catastrophe highlights widely unsuspected risks in many schools. "Most academic laboratories are unsafe venues for work or study," wrote safety expert Neal Langerman in the May/June 2009 *Journal of Chemical Health and Safety*. He termed the fatality "totally and unquestionably preventable." Both Patrick Harran, a chemist and director of the U.C.L.A. lab where Sangji worked, and Chancellor Gene Block independently described Sangji's case as a "tragic accident." "As we continue to mourn Sheri's death and grieve for her family, we are determined to rededicate ourselves to ensuring the safety of each and every member of our entire Bruin family," Block said in a statement. U.C.L.A. and other universities instituted reforms and reportedly reviewed their safety procedures.

To the California Division of Occupational Safety and Health (Cal/OSHA), however, the incident was not a mere misfortune. Cal/OSHA uncovered life-threatening safety violations, including lack of proper training and protective clothing. It also found that U.C.L.A. failed to make a required report of a similar, but nonfatal incident with another student more than a year before Sangji's. Had reforms happened after that event, Sangji's fate might have been different. Cal/OSHA imposed nearly $32,000 in fines (uncontested by U.C.L.A.) in her death.

EMERGENCY SHOWERS **are common in school labs, but lack of safety training in academia has contributed to the death of at least one lab worker, who failed to reach a shower to douse her flames.**

GETTY IMAGES

No hard numbers exist on how often such incidents occur in labs because no one tracks them as a distinct category. The American Chemical Society's Division of Chemical Health and Safety is working to get "reliable data," Langerman says. But surveys find incidents to be much more common in academic settings than in industrial labs, says James Kaufman, president of the Laboratory Safety Institute in Natick, Mass. Since 1997 the toll includes deaths of a Cleveland State University professor by electrocution, a Dartmouth College professor by exposure to a lethal chemical and a University of Chicago professor who was probably infected by a fatal pathogen. Most recently, this past January, an explosion in a chemistry lab at Texas Tech University critically injured a graduate student.

Soon afterward, John S. Bresland, who chairs the U.S. Chemical Safety Board, a federal investigative agency, announced the board would send a team to Texas Tech for its first investigation of an academic lab and would begin systematically studying campus incidents. Texas Tech vice president of research Taylor Eighmy said in a statement that the university supported the investigation: "We have an excellent program in

place, yet we believe this incident affords us an opportunity to proactively look at our safety training."

The problem of school lab danger lies in management responsibility, Langerman says. Often in industry an "annual performance review of a supervisor has a line item on safety," he explains, so serious mishaps jeopardize careers. Many academic institutions, Kaufman adds, show "a disregard that runs from the top of the organization to the bottom," and safety failures rarely damage powerful professorial careers involving large grants. "Do funding agencies like the National Institutes of Health and the National Science Foundation look at the safety and environmental record of the [principal investigator] before they award funding?" Langerman asks. "Do promotion committees look at these things? The answer is no." In addition, occupational safety laws cover employees but not students, and federal standards exempt state workers such as Sangji.

Change will come, Kaufman believes, only when a "culture of safety" akin to that widely cultivated in industry permeates universities and when lab chiefs are held responsible for everyone knowing and following accepted safety practices. Bresland foresees the U.S. Chemical Safety Board developing recommendations and cites interest expressed at meetings of such bodies as the American Chemical Society and the National Academies' Board on Chemical Sciences and Technology. Congress is considering the Protecting America's Workers Act, which would, if passed, extend federal OSHA protection to state employees.

Experience supports the possibility of change. Regulatory reforms made protection of experimental animals and human subjects conditions for receiving federal funding. Similar actions could go a long way to ensuring the safety of the people who do the hands-on work of science.

Beryl Lieff Benderly, a fellow of the American Association for the Advancement of Science, writes frequently about early career and labor issues in science.

Martin Gardner, 1914–2010

COURTESY OF "CARD COLM" MULCAHY *Spelman College*

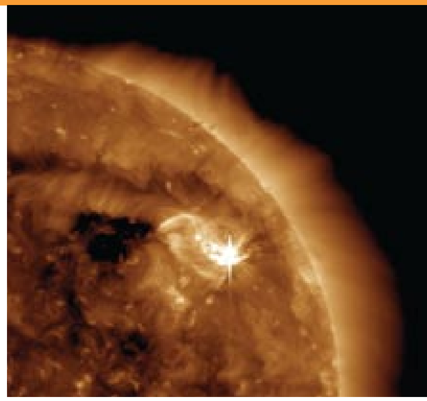
For 25 years Martin Gardner entertained and educated readers of this magazine with his influential Mathematical Games column. For a profile of his work, an online version of his last *Scientific American* article and remembrances by admirers, go to our tribute page at **www.ScientificAmerican.com/aug2010/Gardner**

An Extra Quiet Sun

A long and pronounced solar minimum befuddles astronomers

BY JOHN MATSON

MIAMI—In rough terms, the sun's activity ebbs and flows in an 11-year cycle, with flares, coronal mass ejections, and other energetic phenomena peaking at what is called solar maximum and bottoming out at solar minimum. Sunspots, markers of magnetic activity on the sun's surface, provide a visual proxy for the cycle's evolution; they appear in droves at maximum and all but disappear at minimum. But the behavior of our host star is not as predictable as all that—the most recent solar minimum of late 2008 was surprisingly quiet and prolonged.



SOLAR FLARE (*white*) erupts on the sun, as seen in extreme ultraviolet. Such activity was strangely absent in late 2008, when the sun was quiet for an extended period.

COURTESY OF SOLAR DYNAMICS OBSERVATORY AND NASA

Solar physicists have offered a number of mechanisms to shed light on the solar cycle. Beyond improving fundamental scientific understanding, better predictions of solar behavior would help safeguard against electrical grid disruptions, damage to Earth-orbiting satellites and radiation threats to astronauts. In a press conference at the semiannual meeting of the American Astronomical Society in May, researchers laid out different approaches to tracking and predicting the sun's activity, but the final explanation—or, more likely, explanations—for the sun's curious recent lull remained opaque. "I think we're almost in violent agreement that this is an interesting minimum," said David Hathaway of the NASA Marshall Space Flight Center in Huntsville, Ala.

By several measures the minimum was the deepest on record, although some of those records contain just a few cycles. Hathaway's research focused on shifting speeds of the meridional flow, which moves from the solar equator toward the poles, finding that the flow was anomalously fast at the most recent minimum. But he cautioned against leaping to any conclusions based on a small number of cycles.

The solar jet stream, a slow current originating at solar midlatitudes that pushes toward both the equator and the poles, provides a different window into the sun's roiling innards. Frank Hill of the National Solar Observatory in Tucson examined the periodic nature of the jet stream, which seems to correspond to the onset and end of the solar cycle. With helioseismology data, which track acoustic oscillations on the sun, researchers can follow the development of the jet stream thousands of kilometers below the sun's surface, potentially allowing for better forecasts of the timing of the solar cycle. But it is still too early to tell if the technique can robustly predict solar activity, Hill acknowledged, noting that the stream could be a cause or an effect of the cycle.

A third scientist used helioseismology to look at minima in acoustic oscillations that often correspond with sunspot minima. Yet another turned to magnetic maps to chart the shifting flux across the sun.

After hearing of all these approaches, Hill took stock of a field with many open questions. "My main impression of all this is I'm gratified to see that we all agree that this is an interesting minimum," he said. "What's not so gratifying is we have no clue why any of these effects are happening."

Night Sight: Rapid Eye Movements Seem to Scan the Actions in Our Dreams

Our eyes swivel restlessly in their sockets during rapid eye movement (REM) sleep—a phenomenon that has escaped explanation for decades. Research has suggested several possibilities: the eyes roll around to lubricate the inside of the eyelids; eyes jiggle to warm the brain; eyes twitch in response to stimulation from the brain stem. According to a study in the June issue of *Brain,* the most likely explanation is that our eyes orient their gaze to scan the imagery of our dreams—just as eyes change their gaze in response to our environment when we are awake and moving around.

In the study, neuroscientists at Pitié-Salpêtrière Hospital in Paris turned to a unique group of subjects: those with REM sleep behavior disorder. Such individuals do not enter the standard state of temporary paralysis that prevents any flailing about during dreams. Instead they physically act out their dreams: they kick, scream, grab, reach, climb and jump, enabling researchers to observe what normally remains inside a dreamer's head. "It's a direct window on people's dreams," says Isabelle Arnulf, a neurologist who specializes in sleep and a coauthor of the study. "It's kind of like having movie subtitles."

Arnulf and her colleagues used electrodes to track the eye movements of 56 sleep disorder subjects and 17 normal sleepers, simultaneously videotaping their nocturnal behaviors. The researchers analyzed the nighttime footage of the patients frame by frame to see if their actions and gazes matched up.

And evidently they do. For 90 percent of the time, the gaze of a person with REM sleep disorder synchronized with mimed dream actions. A subject who dreamed of kissing someone to her left also looked to her left. Another participant who dreamed of climbing a ladder shifted his gaze up and down repeatedly to check his progress. Still another glanced over his shoulder as he ran from imaginary lions. If rapid eye movements were truly random twitches, then they would not match their accompanying dream actions so frequently, the researchers conclude. Apparently, when it comes to the neuroscience of dreaming, it's best to believe your eyes.

—Ferris Jabr

GAVRIEL JECAN *Getty Images*

MEDICINE & HEALTH

Hereditary Acquisitions

Acquired diseases that get passed on highlight epigenetic forces in human health BY JR MINKEL

ONE OF THE PRIMARY goals of genetics over the past decade has been to understand human health and disease in terms of differences in DNA from person to person. But even a relatively straightforward trait such as height has resisted attempts to reduce it to a particular combination of genes. In light of this shortcoming, some investigators see room for an increased focus on an alternative explanation for heritable traits: epigenetics, the molecular processes that control a gene's potential to act. Evidence now suggests that epigenetics can lead to inherited forms of obesity and cancer.

The best-studied form of epigenetic regulation is methylation, the addition of clusters of atoms made of carbon and hydrogen (methyl groups) to DNA. Depending on where they are placed, methyl groups direct the cell to ignore any genes present in a stretch of DNA. During embryonic development, undifferentiated stem cells accumulate methyl groups and other epigenetic marks that funnel them into one of the three germ layers, each of which gives rise to a different set of adult tissues. In 2008 the National Institutes of Health launched the $190-million Roadmap Epigenomics Project with the goal of cataloguing the epigenetic marks in the major human cell types and tissues. The first results could come out later this year and confirm that different laboratories can get the same results from the same cells, says Arthur L. Beaudet of the Baylor College of Medicine, the project's data hub. "One couldn't automatically assume it would be so nice," he says.

Up to this point, the best way to study epigenetic effects has been a strain of mice known as agouti viable yellow. In these mice, a retrotransposon—a bit of mobile DNA—has inserted itself in a gene that controls fur color. Mice bearing the identical gene can be yellow or brown depending on the number of methyl groups along the retrotransposon. Such methylation marks would normally be erased in the reproductive cells of an animal. But in 1999 a group led by geneticists at the University of Sydney in Australia discovered that methylation of the fur color genes persists in the female germ line, allowing it to be passed down to offspring like a change in the DNA.

Agouti viable yellow mice might have something to say about the human obesity epidemic. The animals have a tendency to overeat and become obese. In 2008 Robert A. Waterland, also at Baylor, discovered that this trait gets passed down and amplified from one generation of agouti to the next, so that "fatter mothers have fatter offspring," he says. He is investigating whether the effect can be explained in terms of methylation patterns in the hypothalamus, the part of the brain that regulates appetite.

ADAM GILLUM

GENETICALLY IDENTICAL mice bred to have kinked tails can still be born with straight ones because of a process called methylation, which can be affected by a mother's diet.

Retrotransposons could lead to other epigenetic effects. In the early 2000s geneticist David Martin of Children's Hospital Oakland Research Institute in California reasoned that the silencing mechanism that keeps retrotransposons inactive might randomly shut down genes that are supposed to be left on. If the silencing occurred in a gene responsible for suppressing tumor formation, the result would appear the same as genetic mutations that predispose people to cancer.

Working with colleagues at St.

Vincent's Hospital in Sydney, Martin identified two individuals who had the characteristics of hereditary nonpolyposis colorectal cancer, which is usually caused by a mutation that inactivates one of a person's two copies of the tumor suppressor gene *MLH1,* but who showed no signs of mutation. Instead the *MLH1* of both was methylated in cells of the blood, hair follicles and inner cheek—all derived from different embryonic layers.

In Martin's view, the result strongly suggested that the patients had inherited the silenced gene from one of their parents, like the case with agouti mice. Although some researchers have suggested that a genetic mutation in the fertilized egg cell could be responsible for the methylation pattern, Martin says the simplest explanation is an inherited epimutation. "Nobody has been able to explain why these things aren't actually germ-line epimutations," he says.

If epimutations can happen, the same effect should turn up in other genes. Martin's colleague Catherine Suter of the Victor Chang Cardiac Research Institute in Sydney is studying whether melanoma patients have epimutations in genes associated with the cancer. It is also conceivable that epimutations could play a role in some cases of autism, Beaudet says.

Researchers agree they are just scratching the surface of understanding the role of epigenetics in health and disease. The NIH Roadmap Project should help by allowing them to compare models of disease with reference samples. In effect, "we're trying to figure out how we work," says epigenetics researcher Randy Jirtle of Duke University. "It's an amazingly huge project, and it'll never go away."

JR Minkel is a freelance science writer based in Nashville, Tenn.

Worts and All

False claims still pervade the supplements industry BY KATHERINE HARMON

AMERICANS SPENT $14.8 billion in 2007 on herbal supplements and other natural health products, even though numerous recent studies have shown that ginkgo, echinacea, St. John's wort and others are relatively ineffective against many of the ills they have claimed to help. A recent investigation by the Government Accountability Office, part of which employed undercover senior citizens, has revealed how loose regulations and questionable sales tactics are more persuasive than science, potentially putting consumers' health at risk.

The U.S. Food and Drug Administration regulates all dietary supplements as food products under the 1994 Dietary Supplement Health and Education Act, which says that the manufacturers are only responsible for making sure a supplement is safe and meets efficacy claims. But supplement makers are not required to present any information about how they arrived at these conclusions. And although makers cannot claim a product will cure, treat or prevent a specific condition, labels on their products can boast of general body function improvements, such as "aids digestion," "improves heart health" or "boosts brain function," says Paul G. Shekelle, an internist and director of the Southern California Evidence-Based Practice Center at RAND.

These label claims must be followed by a standard FDA disclaimer, but people often do not get the right message, Shekelle says. He notes that "those distinctions can be confusing to consumers," who often might not have all the information to separate body-function statements ("boosts brain function") from specific treatment indications that they might be seeking ("prevents Alzheimer's").

Moreover, messages can get mixed when a sales associate steps in to interpret claims for consumers. The GAO sent undercover staff members to ask common questions of supplement retailers, using consumers over the age of 65 because most of them take prescription medication with which a supplement could interact. The seniors' inquiries included: Is ginkgo biloba safe to take with aspirin? Can ginseng fend off cancer? What about replacing prescribed blood pressure medication with garlic supplements?

The queries got resounding yes's from supplement sales staffs, the GAO found—but they are big no's per the National Institutes of Health. A combination of ginkgo and aspirin can increase the risk of internal bleeding. Ginseng has not been scientifically proved to cure any diseases and should be avoided for those with breast and uterine cancers, according to the NIH. Garlic has not been shown to significantly lower high blood pressure—and supplements are not intended to replace prescribed drugs.

The statements by supplement sales staff amount to "unequivocal deception," argues Marcus M. Reidenberg, chief of the division of clinical pharmacology at New York–Presbyterian Hospital/Weill Cornell Medical Center. Both the FDA and the Federal Trade Commission found the practices "improper and likely in violation of statutes and regulations," stated the GAO report, which was delivered as testimony to Congress on May 26.

The supplement industry's defense came from Steve Mister, president and chief executive officer of the Council for Responsible Nutrition, one of several supplement trade groups. In congressional testimony, he noted that "making false or misleading statements about a dietary supplement in a consumer transaction violates many states' consumer protection, antifraud and unfair competition statutes." He also added that he was not sure "whether the retailers in the GAO's investigations are aware that they are breaking the law."

As Shekelle sees it, the big question is not whether customers should want to spend their money on products of questionable efficacy but whether "taking this stuff is going to be deleterious

to their health." Of the 40 herbal supplements tested for the GAO investigation, 37 contained trace levels of at least one hazardous compound. Other analyses have found contaminants that include steroids and even active pharmaceuticals, Shekelle points out. "This goes back to the presumption that dietary supplements are safe," he says.

To be sure, the contaminants and questionable marketing practices are no surprise to those who have followed this topic in recent years. But the GAO report gives new weight to the issue, which is likely to come up in any congressional debate on food safety. The supplement industry will probably fight additional regulation, which Mister called burdensome, noting that the industry associations have stepped up their efforts to improve inspection and regulation of member companies.

TECHNOLOGY

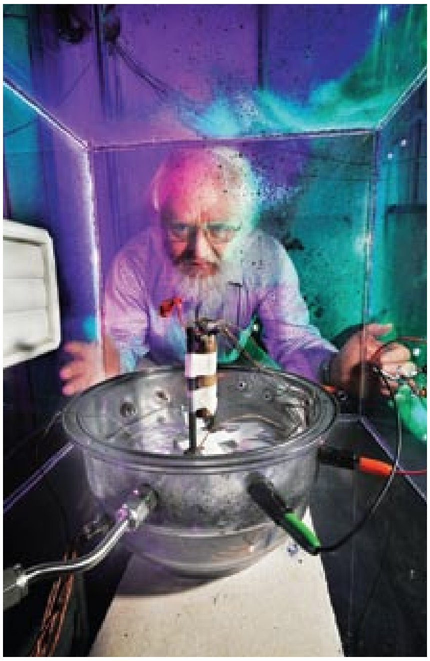
Charge under Control

As lithium-ion batteries take the car market, safety gets lab-tested BY MARK FISCHETTI

THE FORTHCOMING Chevy Volt and Nissan Leaf rely on lithium-ion battery packs, as do other contenders on the electric-car circuit. Yet perhaps mindful of a few highly publicized fires touched off by early lithium-ion power packs in laptops, are consumers assured that their car batteries will remain safe, even in an accident?

Much of the assurance falls under the purview of Sandia National Laboratories' Battery Abuse Testing Laboratory, which has become the de facto automotive battery-testing shop in the U.S. The lab heats, shocks, punctures and crushes batteries to see how safe they would be in crashes and extreme operating conditions.

When lithium-ion cells first came to the laptop market, "the active materials were very energetic. There were some significant field failures," notes Chris Orendorff, the battery lab's team leader. The usual cause was thermal runaway, a chemical reaction that could start from excessive overheating, then potentially cause a cell to catch fire or explode. Although even extreme driving con-



COURTESY OF RANDY MONTOYA *Sandia National Laboratories*

READY, SET, BLOW: In a battery safety test, Sandia researcher Peter Roth prepares to overcharge a lithium-ion cell until it explodes.

ditions are unlikely to trigger those problems, a crash could, and so could a sudden overcharge—for example, if lightning struck a charging port while a car was being recharged.

Small tweaks in chemistry can make a large difference in how well battery packs resist overheating or exploding. "Half a dozen different chemistries are still being considered as viable" in terms of performance and safety, Orendorff says. Sandia is seeing more designs with lithium iron phosphate cathodes, for example, because they stay cool and suffer little degradation over time. Additionally, batteries with anodes made from lithium titanate seem less likely to overheat even under hot driving conditions. Electrolytes containing different lithium salts are still being tested for greatest stability, too.

Manufacturers are also testing a variety of mechanical safety features similar to measures developed to prevent thermal runaway in laptop lithium batteries. Among them are vents that discharge gases that build up during errant reactions and current-interrupt devices that trip like circuit breakers to disable overly active cells.

After years of experimentation, progress in fabricating and testing advanced batteries for fuel-efficient vehicles has accelerated in part because millions of research dollars were appropriated under the 2009 American Recovery and Reinvestment Act. Sandia recently received $4.2 million of stimulus money for upgrades that will allow it to test more batteries and do it faster.

Of course, Sandia and the manufacturers want to prevent all possible dangers. But, Orendorff asserts, consumers forget that no car is completely hazard-proof. Lithium-ion batteries may have a higher chance of igniting than, say, standard lead-acid batteries, "but the chances of flammability are far less than what you have in a combustion vehicle that is carrying 15 gallons of gasoline onboard."

ANYBOTS'S QB can be your robotic avatar.

COURTESY OF ANYBOTS

Robot Test Drive

Your Web-enabled mechanical stunt double is ready BY LARRY GREENEMEIER

IT MAY LOOK like a floor lamp mounted on a vacuum cleaner, but Anybots, Inc.'s new "QB" is actually the latest in surrogate robotics. It is designed to serve as your eyes, ears and voice when you can't be there in person. Even better, it rolls around on two wheels like *The Jetsons*' Rosie and can be navigated remotely via the Web and a Wi-Fi connection.

Anybots formally unveiled the robot on May 18 and plans to start selling QBs this fall, at a hefty $15,000. A five-megapixel video camera serves as one eye, while a laser pointer fills the other spot. A speaker on the crown of a QB's head gives it a mouthpiece, a touch-screen monitor on its forehead enables software maintenance and other input, and a ring of protective rubber around its head makes it look a bit like Olivia Newton-John circa 1981.

Anybots believes its technology will appeal to a new generation of workers who expect to be in contact at all times and in all places. To see how this might work in practice, *Scientific American* test-drove (from our editorial offices in New York City) a QB located at Anybots's facility (in Mountain View, Calif.).

Once our robot "woke up" and connected to Anybots's local Wi-Fi network, we used the arrow keys on our keyboard to navigate the QB across the lobby. The QB features a built-in LIDAR (*l*ight *d*etection *a*nd *r*anging) system for collision avoidance and has a camera located on the bottom of its "chin" that points down at its wheels so you can see whether you are about to drive over a lower obstacle (such as someone's foot).

We drove the QB around, asked another model for directions and performed a laser-tag handshake with Anybots CEO Trevor Blackwell. By the time we were ready to leave, we felt confident enough to drive our QB back to the Anybots lobby and out the front door. Just past the building's threshold, we learned a valuable lesson in surrogate navigation: never drive outside the range of your Wi-Fi network. A dropped connection means no cameras and no control over the robot, which was especially unfortunate in our case because we were approaching a ramp heading down to the parking lot. Thankfully, Anybots's human workers were around to avert disaster.

For a video of the test drive, go to **ScientificAmerican.com/aug2010/anybot**

NASA's Plan to Use Commercial Rockets Lifts Off

Private access to space took a giant leap forward on June 4 with a successful test launch of the Falcon 9 rocket, developed and built by SpaceX, a venture headed by PayPal co-founder Elon Musk.

The two-stage Falcon 9, which stands 48 meters tall, lifted off from Cape Canaveral carrying a dummy capsule that could soon deliver supplies to the International Space Station—and, one day, even astronauts to orbit.

Hopes are especially high for SpaceX in light of President Barack Obama's 2011 budget request, which calls for NASA to terminate its own line of Ares rockets and instead to contract with private operators. In 2008 NASA had announced that it ordered 12 flights from SpaceX to resupply the space station through 2016, at an estimated cost of about $1.6 billion. *—John Matson*

2010

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Catastrophic Thinking

The way to avoid ruinous oil spills is to fix our national energy policy

BY THE EDITORS

The oilmen were drilling deep below the Gulf of Mexico when a rise of pressure from natural gas blew out the wellhead. A safety device intended to seal the well failed, and tens of thousands of barrels of oil a day began to shoot up into the Gulf waters. Engineers tried stopping the flow with mud and junk and lowering a cap over the leak. They spent months digging relief wells to plug the hole. Eventually they stanched the flow, but it took the better part of a year and contaminated the waters with millions of barrels of crude. Fisheries had to close, birds and other wildlife perished, and vast lengths of coastline were soiled.

That catastrophe happened in 1979, when the Ixtoc 1 drilling rig sank. The parallels between its demise and the Deepwater Horizon disaster that began in April are chilling. We do not know how the ongoing story will end, and we may never be certain what happened in the ocean depths. That two events 30 years apart have followed nearly the same script shows we—not just the oil industry but the entire nation—have failed to address the underlying reasons for these debacles.

In the intervening decades, the oil industry has made huge technological advances. Sophisticated imaging and steerable drills let drillers extract a larger fraction of the available oil at far greater depths and leave less of a footprint on the surface than ever before [see "Squeezing More Oil from the Ground," by Leonardo Maugeri; Scientific American, October 2009]. Based on these innovations, oil companies have made the case for opening up more coastal areas and the Arctic wilderness to drilling, and they have gotten a sympathetic hearing in Washington, D.C.

Unfortunately, the less sexy human side of the equation has not gotten the same attention. The number of snafus that led to the latest calamity is breathtaking: time-stressed managers who cut corners, regulators who were literally in bed with the industry, politicians who hurried along an ideological agenda of deregulation.

How does an industry organize itself into teams of engineers and technicians across thousands of rigs and dozens of companies, to reach oil trapped in increasingly forlorn places, in a way that is robust enough to tolerate human error? It is not easy, but it can be done. High-tech, high-risk enterprises as diverse as nuclear power stations and U.S. Navy aircraft carriers have learned to keep accident rates remarkably low. Accidents may be inevitable, but the chance of catastrophe should be nearly zero.

The first step is to make realistic assessments of risk at the outset. That may seem obvious, yet it is not routinely done for deepwater drilling. In documents BP submitted to its regulators at the U.S. Minerals Management Service, the company downplayed the risk, says Robert Bea, a petroleum engineer at the University of California, Berkeley, who spent decades as an engineer in the oil industry, including a stint at BP. "We went into this with our eyes partly closed," he says. "We've excluded from our thinking these nightmares, and we haven't honored the Boy Scout's motto: be prepared."

Second, government oversight needs an overhaul. The Minerals Management Service has been chronically underfunded and has systematically ignored the advice of its own scientists, let alone independent researchers. Even before the Deepwater Horizon sank, the Obama administration had planned a reorganization of the agency. It is not the regulator's role to keep BP from betting the company on a single well but to make sure it does not bet the entire Gulf of Mexico along with it.

Finally, if we expect oil companies to manage risk better, then society as a whole needs to do the same. The market forces that encouraged BP to take ill-considered risks are largely of our own creation, as stockholders, consumers and citizens. The hodgepodge of subsidies that masquerades as our current national energy policy invites disaster; it fails to grapple with the urgent need to stop wasting energy and start encouraging clean sources. Every day we still need 85 million barrels of oil—the equivalent of more than 25 Ixtoc spills—to keep the wheels of our society turning. President Barack Obama is entirely correct to speak of the giant slick now oozing around Florida as another reason for a comprehensive energy policy.

Pundits and politicians have criticized the president for being slow to respond to the disaster, but that criticism misses the mark. The point is not to respond but to anticipate. Once again, Deepwater Horizon has proved the sad maxim that it takes a crisis to focus attention on an issue. Maybe we can finally learn now what we should have learned 30 years ago: that we should not just be mopping up the last crisis but preventing the next one, whether it is an oil-rig blowup or ice sheets calving into the sea. ■

ILLUSTRATION BY MATT COLLINS

© MedicalRF.com/Getty Images.

Market Reforms, 20 Years Later

Economic, political and cultural forces have boosted Poland but fallen short in Russia

BY JEFFREY D. SACHS

I recently had the pleasure to revisit Warsaw, Poland, and St. Petersburg, Russia, two decades after the start of market reforms in which I had participated as an economic adviser. Both cities, proud and venerable capitals, had surmounted the tumultuous collapse of the Soviet era. Shops were full; architectural treasures glistened; local and international tourists abounded.

Yet the differences were also apparent. Warsaw has enjoyed a building boom, with impressive new business towers going up despite the economic slowdown in western Europe. St. Petersburg glories in the architectural treasures of the past but with much less evidence of current dynamism.

Because I worked in the late 1980s and early 1990s throughout eastern Europe and the former Soviet Union, I have often been asked since then why market reforms took stronger hold in some places than others. The answers, rooted in the complex interplay of geography, politics, history and culture, are well worth understanding.

The greatest dividing line in outcomes has been the Soviet border. Countries such as Poland, Hungary, the Czech Republic and Slovakia—which had been outside of the Soviet Union but under Soviet domination—were eager to dash toward membership in the European Union. That membership process usefully steered their internal politics and legal reforms and prompted incoming foreign investments from Germany, Italy, Austria and Scandinavia.

Conversely, Russia was not dashing to Europe but was instead grappling with its own past and future. The collapse of the Soviet system was not followed by a consensus on a new economic and political model within Russia to replace it. Russian statecraft continued to be guided by the centuries-old practice of bureaucratic rule that cast a wary eye on market forces.

Culture has also shaped the dynamics of reform. Because Poles maintained a healthy skepticism toward state power, Poland developed a vigorous and competitive democracy after 1989. Civil society energetically criticized state corruption and helped to keep it in check. Out of 180 countries evaluated by the organization Transparency International for its latest index of perceived public-sector corruption, Poland stands as the 49th least corrupt. This ranking is not as high as it should be but is still rather good for a middle-income, young democracy that has so recently emerged from decades of Communist rule.

In Russia, on the other hand, corruption has run rampant during the past 20 years, and the public shows little capacity to rein it in. The institutions of civil society, suppressed by centuries of tsarism and obliterated by Soviet-era state brutality, remain weak. Because the constraints on corruption were so toothless, vast state wealth—especially oil, gas and mineral wealth—was transferred in the mid-1990s into private hands, creating the so-called oligarchs of the new Russia. A few years later powerful bureaucrats wrested back control of many of these assets. The rise and fall of the oligarchs was murky, without the transparency needed for a healthy market economy. Russia, not surprisingly, lands at a dismal 146th on the Transparency International corruption list.

One of the sad parts of the story was the failure of U.S. presidents George H. W. Bush and Bill Clinton to support Russia's embattled reformers at crucial moments. I have come to believe that senior American officials were insensitive to the growing Russian corruption and remained passive when they could have helped reformers to keep it in check. After all, the U.S. has its own corruption problems, ranking a rather dreary 19th on the Transparency International list, below most other high-income countries.

I left St. Petersburg feeling that so much more economic reform was still possible in that glorious city and throughout Russia. The people's high education and technical expertise do not adequately translate into new businesses and higher incomes. The bureaucracy keeps its traditional grip, even maintaining the internal registration system from the time of the tsars that constrains Russians from moving from city to city. Small businesses are similarly encumbered with arbitrary regulations. Russia's gains in political and economic liberalization are undoubted, but this country with so much talent has yet to combine the best of its cultural heritage, its technical skills and the advantages of greater economic freedom. ■

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.ScientificAmerican.com/aug2010**

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

Our Neandertal Brethren

Genome sequencing has revealed our common humanity

BY MICHAEL SHERMER

According to the late Harvard University biologist Ernst W. Mayr, the greatest evolutionary theorist since Charles Darwin, "species are groups of actually or potentially interbreeding natural populations which are reproductively isolated from other such groups."

Reproductive isolation is the key to understanding how new species form, and many types of barriers can divide a population and split it into two different groups: geographic (such as a mountain range, desert, ocean or river), morphological (a change in coloration, body type or reproductive organs), behavioral (a change in breeding season, mating calls or courtship actions), and others. After isolation, if members of the split populations encounter one another and cannot produce viable offspring that can themselves later successfully interbreed and produce viable offspring (hybrids such as mules are infertile), then these two populations constitute two different species.

Let's say that a species migrates out of Africa into Europe around 400,000 years ago and becomes reproductively isolated from its ancestral population for the next 320,000 years. It evolves distinctive anatomical features and adaptations for the colder climes. Moreover, even after other descendants of the original ancestral population move into Europe around 80,000 years ago, the skeletons from both groups show no obvious signs of blended characteristics. Modern scientists classify the creatures as two different species.

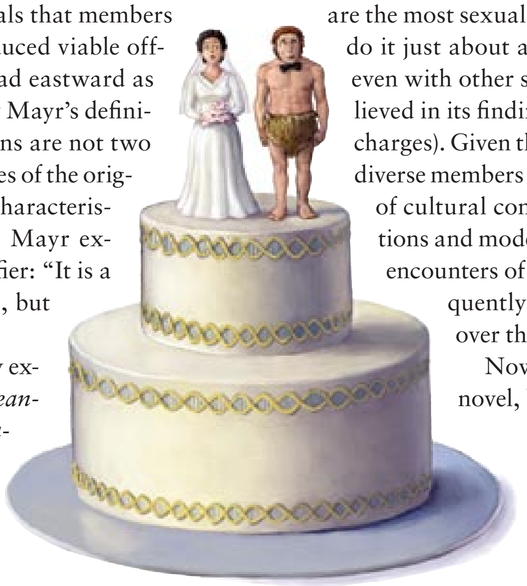
Then, however, genetic analysis reveals that members of these two species interbred and produced viable offspring that populated Europe and spread eastward as far as China and Papua New Guinea. By Mayr's definition, these two interbreeding populations are not two species after all, but two sibling subspecies of the original African species. A subspecies has a characteristic appearance and geographic range, Mayr explains, yet he adds this significant qualifier: "It is a unit of convenience for the taxonomist, but not a unit of evolution."

Thus it is—revealing the identity of my example—that we must reclassify *Homo neanderthalensis* as *Homo sapiens neanderthalensis,* a subspecies of *Homo sapiens*. A comprehensive and technically sophisticated study published in the May 7 issue of *Science,* "A Draft Sequence of the Neandertal Genome," by Max Planck Institute evolutionary anthropologists Richard E. Green, Svante Pääbo and 54 of their colleagues, demonstrates that "between 1 and 4% of the genomes of people in Eurasia are derived from Neandertals" and that "Neandertals are on average closer to individuals in Eurasia than to individuals in Africa." In fact, the authors note, "a striking observation is that Neandertals are as closely related to a Chinese and Papuan individual as to a French individual.... Thus, the gene flow between Neandertals and modern humans that we detect most likely occurred before the divergence of Europeans, East Asians, and Papuans." In other words, our anatomically hirsute cousins are actually our genetic brothers.

This modified Out of Africa theory holds that around 400,000 years ago a population of hominids migrated northward through the Middle East and into Europe and parts of western Asia. Between 80,000 and 50,000 years ago another population from the ancestral continent journeyed a similar route into the Eurasian landmass, and there the two populations met and mated. We are their descendants. The Neandertal species did not go extinct, because it was never a separate species; instead population pockets of Neandertals died out around 30,000 years ago, whereas other Neandertal populations survived through interbreeding with their modern human brothers and sisters, who live on to this day.

I always suspected that Neandertals and anatomically modern humans interbred, based on a simple observation: humans are the most sexual of all the primates, willing and able to do it just about anywhere, anytime, with anyone (and even with other species if the Kinsey report is to be believed in its findings about farmhands and their animal charges). Given the viable hybrid offspring that the most diverse members of our species have produced as a result of cultural conjoinings through both ancient migrations and modern travel, one has to suspect that close encounters of the corporeal kind occurred not infrequently in those dark and lonely cave nights over the course of those long-gone millennia.

Now *that* is a tale worthy of a romantic novel, brought to you by science. ■



Michael Shermer is publisher of Skeptic *magazine (www.skeptic.com) and author of* Why Darwin Matters.

PHOTOGRAPH BY BRAD SWONETZ; ILLUSTRATION BY MATT COLLINS

Faith and Foolishness

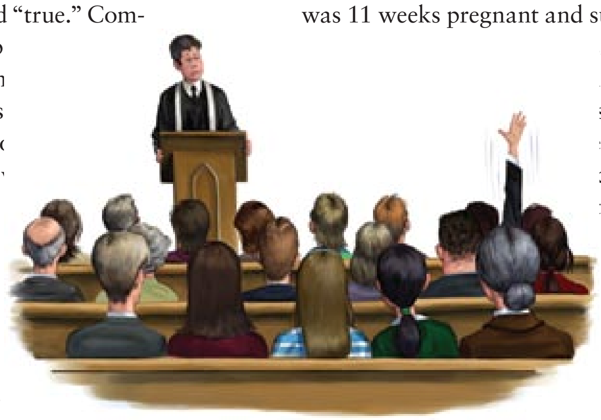
Religious leaders should be held accountable when their irrational ideas turn harmful

BY LAWRENCE M. KRAUSS

Every two years the National Science Foundation produces a report, *Science and Engineering Indicators,* designed to probe the public's understanding of science concepts. And every two years we relearn the sad fact that U.S. adults are less willing to accept evolution and the big bang as factual than adults in other industrial countries.

Except for this time. Was there suddenly a quantum leap in U.S. science literacy? Sadly, no. Rather the National Science Board, which oversees the foundation, chose to leave the section that discussed these issues out of the 2010 edition, claiming the questions were "flawed indicators of scientific knowledge because responses conflated knowledge and beliefs." In short, if their religious beliefs require respondents to discard scientific facts, the board doesn't think it appropriate to expose that truth.

The section does exist, however, and *Science* magazine obtained it. When presented with the statement "human beings, as we know them today, developed from earlier species of animals," just 45 percent of respondents indicated "true." Compare this figure with the affirmative p Japan (78), Europe (70), China (69) an rea (64). Only 33 percent of Americans "the universe began with a big explosi



Consider the results of a 2009 Pe Survey: 31 percent of U.S. adults believe "humans and other living things have existed in their present form since the beginning of time." (So much for dogs, horses or H1N1 flu.) The survey's most enlightening aspect was its categorization of responses by levels of religious activity, which suggests that the most devout are on average least willing to accept the evidence of reality. White evangelical Protestants have the highest denial rate (55 percent), closely followed by the group across all religions who attend services on average at least once a week (49 percent).

I don't know which is more dangerous, that religious beliefs force some people to choose between knowledge and myth or that pointing out how religion can purvey ignorance is taboo. To do so risks being branded as intolerant of religion. The kindly Dalai Lama, in a recent *New York Times* editorial, juxtaposed the statement that "radical atheists issue blanket condemnations of those who hold religious beliefs" with his censure of the extremist intolerance, murderous actions and religious hatred in the Middle East. Aside from the distinction between questioning beliefs and beheading or bombing people, the "radical atheists" in question rarely condemn individuals but rather actions and ideas that deserve to be challenged.

Surprisingly, the strongest reticence to speak out often comes from those who should be most worried about silence. Last May I attended a conference on science and public policy at which a representative of the Vatican's Pontifical Academy of Sciences gave a keynote address. When I questioned how he reconciled his own reasonable views about science with the sometimes absurd and unjust activities of the Church—from false claims about condoms and AIDS in Africa to pedophilia among the clergy—I was denounced by one speaker after another for my intolerance.

Religious leaders need to be held accountable for their ideas. In my state of Arizona, Sister Margaret McBride, a senior administrator at St. Joseph's Hospital in Phoenix, recently authorized a legal abortion to save the life of a 27-year-old mother of four who was 11 weeks pregnant and suffering from severe complications he made that decision after consul- with the mother's family, her doc- s and the local ethics committee. Yet bishop of Phoenix, Thomas Olm- d, immediately excommunicated Sis- er Mary, saying, "The mother's life cannot be preferred over the child's." Ordinarily, a man who would callously let a woman die and orphan her children would be called a monster; this should not change just because he is a cleric.

In the race for Alabama governor, an advertisement bankrolled by the state teachers' union attacked candidate Bradley Byrne because he supposedly supported teaching evolution. Byrne, worried about his political future, felt it necessary to deny the charge.

Keeping religion immune from criticism is both unwarranted and dangerous. Unless we are willing to expose religious irrationality whenever it arises, we will encourage irrational public policy and promote ignorance over education for our children. ■

Lawrence M. Krauss, a physicist and science commentator, is Foundation Professor and director of the Origins Initiative at Arizona State University (www.krauss.faculty.asu.edu).

PHOTOGRAPH BY NANCY DAHL-TACCONI; ILLUSTRATION BY MATT COLLINS

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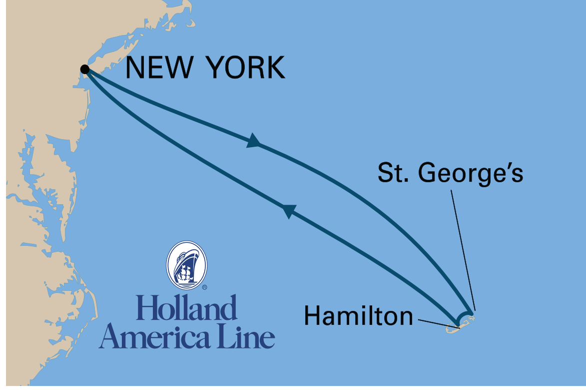

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- Transformed Social Interaction in Virtual Worlds

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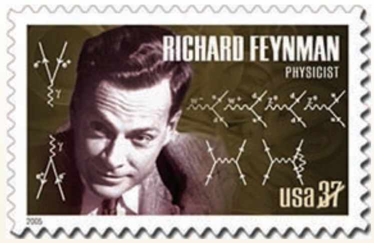
Speaker: **Nancy C. Andreasen M.D., Ph.D.**

- The Brain's Odyssey through Life: Development and Aging Across the Lifespan
- The Creative Brain: The Neuroscience of Genius
- Venus vs. Mars or the Age of Androgyny? Gender and the Brain

RATIONAL THOUGHT — AND NOT
Speaker: **Michael Shermer, Ph.D.**

- The Bermuda Triangle and Other Weird Things that People Believe
- Why Darwin Matters: Evolution, Intelligent Design, and the Battle for Science and Religion
- The Mind of the Market: Compassionate Apes, Competitive Humans, and Other Lessons from Evolutionary Economics



THE INQUIRING PHYSICIST
Speaker: **Lawrence Krauss, Ph.D.**

- Quantum Man: Richard Feynman and Modern Science
- Hiding in the Mirror: The Mysterious Allure of Extra Dimensions
- An Atom from the Caribbean

ARCHAEOLOGY/ANTHROPOLOGY
Speaker: **Jerald T. Milanich, Ph.D.**

- Belle Glade Cultures — Secrets from 500 BC to AD 1700
- Documenting Florida's Seminoles — Adventure Behind the Scenes
- Archaeology of the Spanish Colonial Southeast U.S. After 1492

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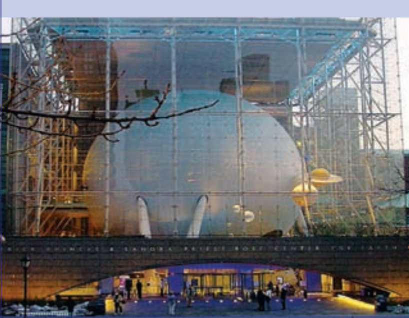
SCIENCE IN NEW YORK CITY

Saturday, May 7, 2011 (optional)

Wake up in the city that never sleeps, as we start at 9am in the Rose Center for Earth and Space (below) at the American Museum of Natural History for a private insiders' tour. During our tour we'll get the inside scoop on research being done at the Rose Center. After our astronomy sojourn, we'll reconvene in lower mid-town Manhattan, at the Scientific American headquarters, for an early evening social reception/dinner with Scientific American staffers.



During our visit, the Curator of the Einstein exhibit, and our day's host, Dr. Michael M. Shara will deliver the following two lectures:

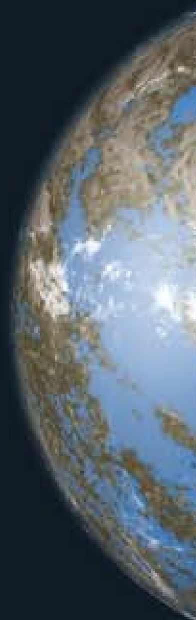
Einstein's Revolution—He was daring, wildly ingenious, passionately curious. He saw a beam of light and imagined riding it; he looked up at the sky and envisioned that space-time was curved. Albert Einstein reinterpreted the inner workings of nature, the very essence of light, time, energy, and gravity. His insights fundamentally changed the way we look at the universe.

10 Discoveries from the Hubble Space Telescope—In the 20 years it has been in orbit, Hubble has revolutionized our understanding of how the universe works. Images from the telescope have become iconic forms of modern art. And lurking in each image is new science. Dr. Shara will describe 10 remarkable discoveries made with the Hubble, and show how its images reveal something we've never seen or understood before.

PLANETS WE COULD CALL HOME

The night skies are littered with distant planets, but what are they really like? Theoretical models suggest that a surprising number of "exoplanets" could be similar to Earth—and may even support life

BY DIMITAR D. SASSELOV AND DIANA VALENCIA



RON MILLER

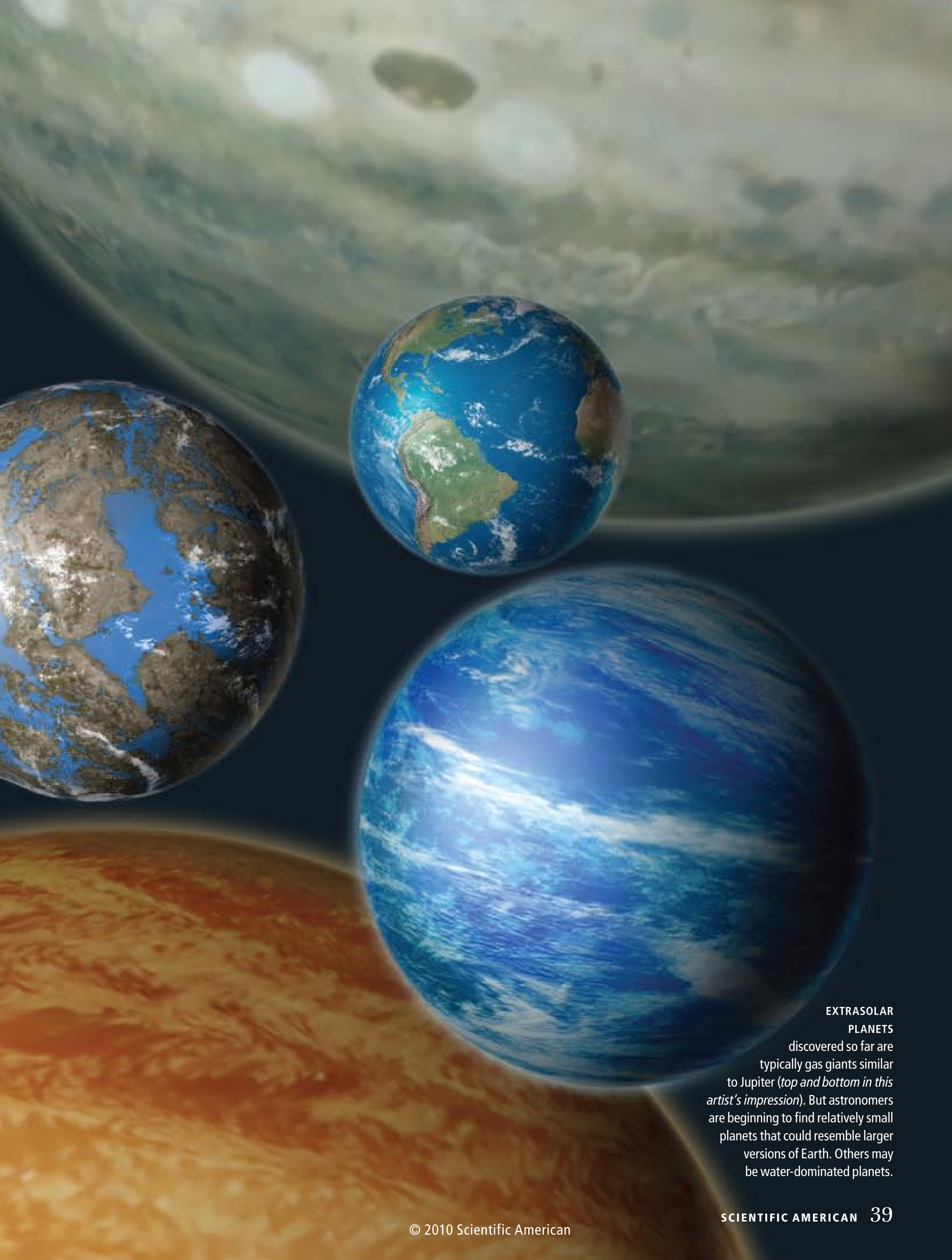
KEY CONCEPTS

- The pace of extrasolar planet discovery is about to explode, thanks to a new space-based observatory.
- Models now predict that rocky planets larger than Earth may have a lively geology and stable atmospheres and climates.
- Some of these "super-Earths" could be hospitable to life.

—The Editors

IMAGINE YOURSELF gazing at the sky on a summer night. You look in the direction of a particular star that, you have heard, has a special planet orbiting around it. Although you cannot actually see the planet—you can barely see the star itself—you know it is several times larger than Earth and, like Earth, is made mostly of rock. Quakes sometimes shake its surface, much of which is covered by oceans. Its atmosphere is not too different from the one we breathe, and its sky is swept by frequent storms and often darkened by the ash of volcanoes. But most of all, you know that scientists think it could harbor life—and that they plan to seek evidence for it.

This scenario could become reality within the next decade. Although most of the 450-odd extrasolar planets found so far are giants more similar to Jupiter, astronomers are beginning to discover some that may not be too different from Earth. And NASA's Kepler probe, a planet hunter sent aloft last year, will discover many more.



EXTRASOLAR PLANETS discovered so far are typically gas giants similar to Jupiter (*top and bottom in this artist's impression*). But astronomers are beginning to find relatively small planets that could resemble larger versions of Earth. Others may be water-dominated planets.

Researchers can deduce a surprisingly detailed portrait of a far-off planet from just a few numbers.

Of course, these worlds are light-years away, so even our most advanced instruments cannot actually see the details of their surfaces—the mountains, the clouds, the volcanoes—and perhaps never will. Usually all our telescopes can do is detect indirect signs of a planet's presence and help us estimate its mass and how wide its orbit is. In some cases, they can also give information about a planet's diameter and perhaps a few other details. In the case of the giant exoplanets, these details may include estimates about the atmospheric composition and wind dynamics.

That is a far cry from being able to measure anything specific about geology, chemistry or other features. Yet from those few numbers, researchers can deduce surprisingly complex portraits of the far-off planets, using theoretical modeling, computer simulations and even laboratory experiments, combined with established knowledge of Earth and other planets of the solar system.

In our research, for example, we have modeled planets with a composition similar to Earth's. We found that such planets, even when they are substantially more massive than our world, should be geophysically active and have atmospheres and climates that might be friendly to life. In fact, we have learned that Earth's mass may be at the lower extreme of the range needed for a planet to be habitable. In other words, had Earth been any smaller, it might have turned out to be as lifeless as Mars and Venus seem to be.

THE FIRST SUPER-EARTHS

THE DREAM of finding planets that could potentially harbor life was what first entwined the careers of this article's authors. The more senior of us (Sasselov) entered the field somewhat serendipitously a decade ago. The first extrasolar planets had been discovered in the mid-1990s, mostly using the "wobble" method, which detects the presence of a planet by its gravitational effects on its star; the body's gravity tugs on the host star, accelerating it in alternating directions, something that can be detected as a shift in the spectrum of light received from the star.

Initially some skeptical scientists wondered whether the wobbles could be caused by a star's physics rather than by orbiting planets. That was how Sasselov—an astrophysicist and thus an expert on stars, not planets—got involved: his specialty was stars that display periodic changes in the way they shine. He helped to settle the wobble issue: the wobble was really caused by planets. Astrophysicists had a powerful tool for hunting exoplanets.

Sasselov then joined a group of scientists who

[SOME REMARKABLE PLANETS]

TOP DESTINATIONS IN THE MILKY WAY

Because larger planets are easier to detect than smaller ones, most of the planets confirmed so far—461 at the time this issue went to press—are very large; some are many times as massive as Jupiter. In most cases, astronomers cannot estimate a planet's radius but can discern its mass and the shape of its orbit. But in some cases, the radii are known, including those of two relatively small planets, GJ1214b and CoRoT-7b.

PLANET: Earth
TYPE: Terrestrial (rocky)
MASS: 1 Earth mass
RADIUS: 1 Earth radius (6,371 kilometers)
ORBITAL PERIOD: 365 days
FEATURES: Active geology—together with the planet's "right" distance from its parent star—helps to keep surface temperatures within the range where liquid water can exist. Known to be quite hospitable to life.

PLANET: GJ1214b
TYPE: Super-Earth
DISCOVERY DATE: 2009
MASS: 6.55 Earth masses
RADIUS: 2.7 Earth radii
ORBITAL PERIOD: 38 hours
FEATURES: One of only two super-Earths whose radii are known. It is more like a mini Neptune, with an ice-and-rock interior and a gaseous envelope.

PLANET: CoRoT-7b
TYPE: Rocky super-Earth
DISCOVERY DATE: 2009
MASS: 4.8 Earth masses
RADIUS: 1.7 Earth radii
ORBITAL PERIOD: 20 hours
FEATURES: The first super-Earth to have its radius measured. It constantly shows the same face to its star, a face so hot that it is permanently molten. Clouds of silica rise there and condense on the permanently frozen dark side.

PLANET: Kepler 7b
TYPE: Gas giant
DISCOVERY DATE: 2009
MASS: 0.43 Jupiter mass
RADIUS: 1.48 Jupiter radii
ORBITAL PERIOD: 4.9 days
FEATURES: The least dense planet discovered so far, it may have a small, rocky core but is mostly, if not all, gas.

RON MILLER (*planets*)

were proposing to build the Kepler space observatory to look for exoplanets. The probe eventually went into orbit in 2009. It is designed to detect planets by tracking small dips in a star's brightness, usually lasting a few hours; if such dips happen at regular intervals, they signify that a planet is in orbit about the star, periodically passing in front of it. The telescope is trained at one particular patch of sky near the constellation Cygnus. Its wide-angle digital camera is monitoring about 150,000 stars for three years straight. Once it has amassed data for long enough, Kepler is expected to find hundreds of new planets, some as small as Earth.

Early in the planning of the mission, Sasselov realized that although Kepler would produce a wealth of information, scientists would not necessarily know what to make of it all. To his surprise, he learned, for instance, that no one had ever tried to model the geologic processes of a large Earth-like planet. So he began a collaboration with Richard O'Connell, a Harvard University expert on Earth's interior dynamics.

At that time, the other of us (Valencia) had started work on her Ph.D. in geophysics at Harvard, intending to focus on seismology, and was taking a geodynamics class being taught by O'Connell. Following a conversation he had with Sasselov, O'Connell asked his class to ponder how the size of Earth would change if it had more mass. How much would the additional gravity compact its innards? The question grabbed Valencia and changed the course of her research career.

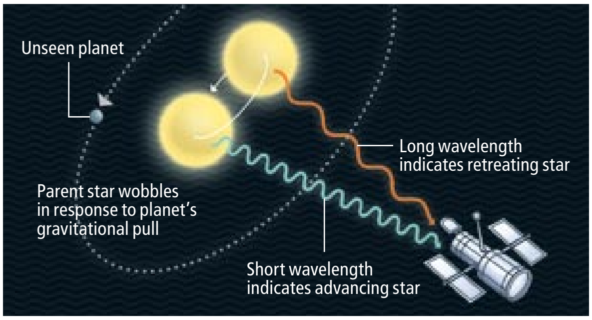
PETER AND MARIA HOEY

[METHODS]

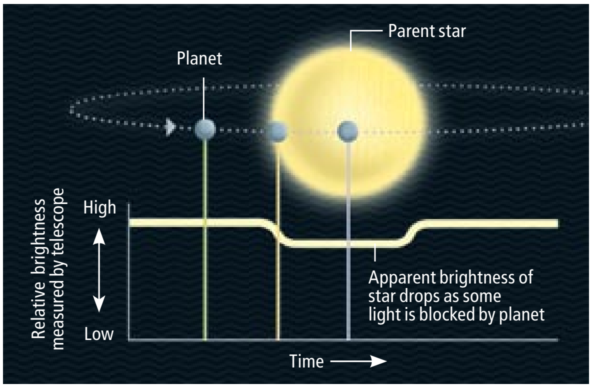
HOW TO SPOT A PLANET

Compared with the stars they orbit, planets are very faint sources of light. Consequently, only a handful of extrasolar planets, all very large and bright, have been "seen" directly—that is, resolved as dots separate from their stars. In some cases, astronomers have detected a planet's colors mixed in with the glare of the parent star. In most other cases, astronomers have found planets only indirectly, usually by applying the "wobble" or "transit" techniques.

WOBBLE METHOD
During a planet's orbit, its gravity pulls on the parent star. By analyzing the spectrum of light from the star, astronomers can measure changes in the star's relative velocity with respect to Earth as small as one meter per second or less. Periodic variations reveal the presence of the planet.



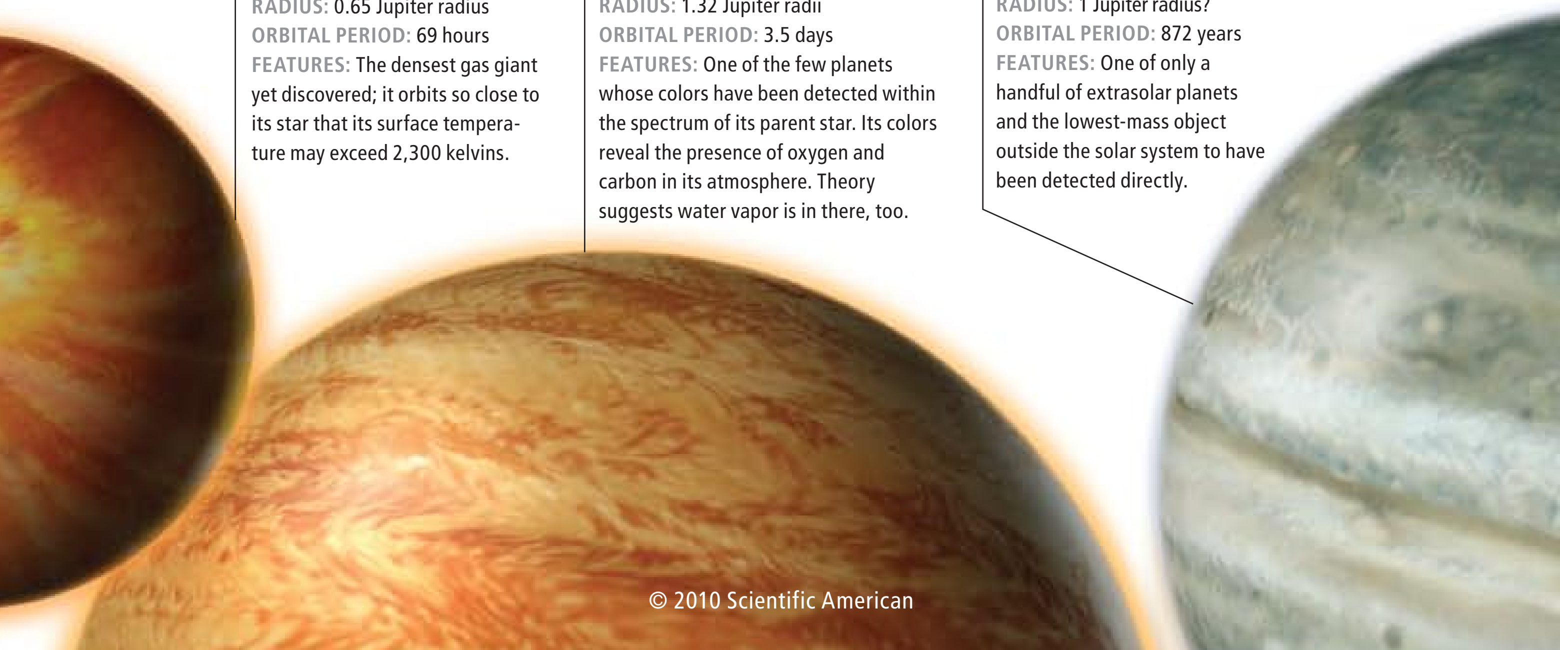
TRANSIT METHOD
If a planet's orbit crosses the line of sight between its parent star and Earth, it will slightly dim the light received from the star, just as a partial lunar eclipse dims the sun. A Jupiter-size planet dims its star by about one percent; for an Earth-size one, the dimming is about 0.01 percent—a change that is within the sensitivity of the new Kepler space telescope [*see box on page 45*].



PLANET: HD149026b
TYPE: Gas giant
DISCOVERY DATE: 2005
MASS: 0.36 Jupiter mass
RADIUS: 0.65 Jupiter radius
ORBITAL PERIOD: 69 hours
FEATURES: The densest gas giant yet discovered; it orbits so close to its star that its surface temperature may exceed 2,300 kelvins.

PLANET: Osiris (HD209458b)
TYPE: Gas giant
DISCOVERY DATE: 1999
MASS: 0.69 Jupiter mass
RADIUS: 1.32 Jupiter radii
ORBITAL PERIOD: 3.5 days
FEATURES: One of the few planets whose colors have been detected within the spectrum of its parent star. Its colors reveal the presence of oxygen and carbon in its atmosphere. Theory suggests water vapor is in there, too.

PLANET: Fomalhaut b
TYPE: Gas giant
DISCOVERY DATE: 2008
MASS: .5 to 3 Jupiter masses
RADIUS: 1 Jupiter radius?
ORBITAL PERIOD: 872 years
FEATURES: One of only a handful of extrasolar planets and the lowest-mass object outside the solar system to have been detected directly.



In our solar system, Earth is the largest of the rocky, or terrestrial, planets. So scientists were not accustomed to thinking of planets with a similar composition but many times the mass—super-Earths, for lack of a better word. The field was so new that when in 2004 our collaboration submitted its first paper on super-Earths for publication, it took the journal editors nearly a year to find scientists with the right expertise to referee it. In fact, early on many planetary scientists were puzzled by our choice of research topic. The only exoplanets discovered until then were Jupiter-class gas giants, not super-Earths. Why would anyone want to study planets that may not exist?

Only months later, in 2005, our efforts were vindicated. Using the wobble method, Eugenio Rivera of the University of California, Santa Cruz, and his collaborators discovered a planet orbiting the star Gliese 876, in the constellation Aquarius. It was the first known super-Earth.

We know that the planet, named GJ 876d, orbits its sun in just two days and that its mass is roughly 7.5 times that of Earth. But that is about all we can say about it. In particular, we have no way to find out GJ 876d's mean density (which is mass divided by volume) and thus to guess its composition, because we cannot measure its size. An orbital transit, however, can reveal size: the extent to which a planet dims the light of the parent star tells you the planet's diameter. If you also measure the wobble, then you have both mass and diameter, and hence you can calculate mean density. If the density is high, like that of rock, your planet could be a rocky one.

The transit method was how, in early 2009, astronomers discovered the first transiting super-Earth, CoRoT-7b, using France's CoRoT space telescope, a smaller predecessor of Kepler. This planet is so dense it is definitely made of rock. It orbits so close to its star—its year lasts less than one Earth-day—that its dayside surface must be permanently molten. (Planets in tight orbits become tidally locked to their stars, so that they always show the same face to it, just like our moon does to Earth.) Hardly 10 months later a ground-based project led by David Charbonneau of the Harvard-Smithsonian Center for Astrophysics discovered a second transiting super-Earth. Dubbed GJ1214b, it is unusual in that it has a density closer to that of water than to that of rock, suggesting that it must have a thick envelope of gas.

Thus, neither planet is anything like ours. We are looking for habitable, Earth-like worlds but seem to encounter monsters. Other oddities are likely to show up as well. For example, around very carbon-rich stars, solid planets would not consist primarily of silicon-oxygen compounds, as is the case of our solar system's terrestrial planets, but of silicon bound to carbon. This would be quite a different kind of planet, with an interior made largely of diamond as a result of the compression of carbon.

But because most solar systems, including ours, have similar compositions, researchers expect that the makeup of most super-Earths will be close to that of Earth—mostly silicon bound to oxygen and magnesium, plus iron and smaller amounts of other elements—often with the addition of vast amounts of water. Soon we will be discovering many such planets, so it is worthwhile to try to learn more about them, beginning with the physics of their interiors.

JOURNEY TO THE CENTER OF A SUPER-EARTH

TWO MAIN CATEGORIES of super-Earths should exist, depending on where in their solar systems the planets formed. Those that formed far enough from the star would have swept up large quantities of primordial ice particles that were orbiting the new star, and water would end up making up a much larger share of the planets' mass than it does in the terrestrial planets of the solar system. On the other hand, planets that formed closer to their stars, where it was too hot for ice to exist, would have ended up relatively dry, like Earth and its fellow terrestrial planets in our solar system.

A rocky planet would start out as a hot, molten mix of material and would immediately begin to cool down by radiating heat into space. Iron- and silicate-based crystals would form in the solidifying magma. Depending on the amount of oxygen, some of the iron would not be incorporated into minerals. This iron would remain in liquid form and, being denser, would sink to the center. Just as with Earth, then, the planet would assume an onionlike structure, with an iron core and a predominantly silicate mantle.

A difference would arise in the cores of larger planets compared with those of Earth-size ones. Inside Earth, over billions of years the core has cooled enough so that the inner part of the core has solidified, whereas the outer core is still liquid, so that it churns in convective currents. The convection of the outer core is believed to be the engine that creates the geomagnetic field.

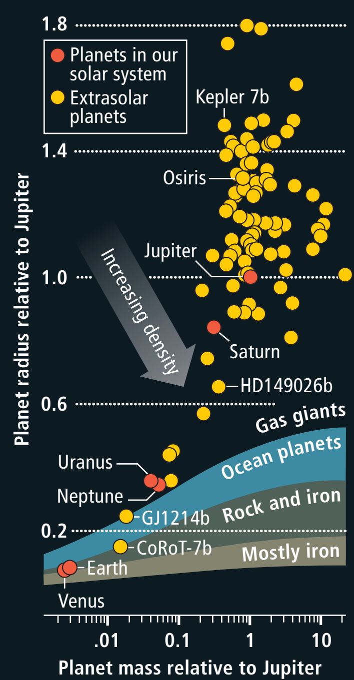
[SIMULATED EXOPLANETS]

BETTER LIFE THROUGH GEOPHYSICS

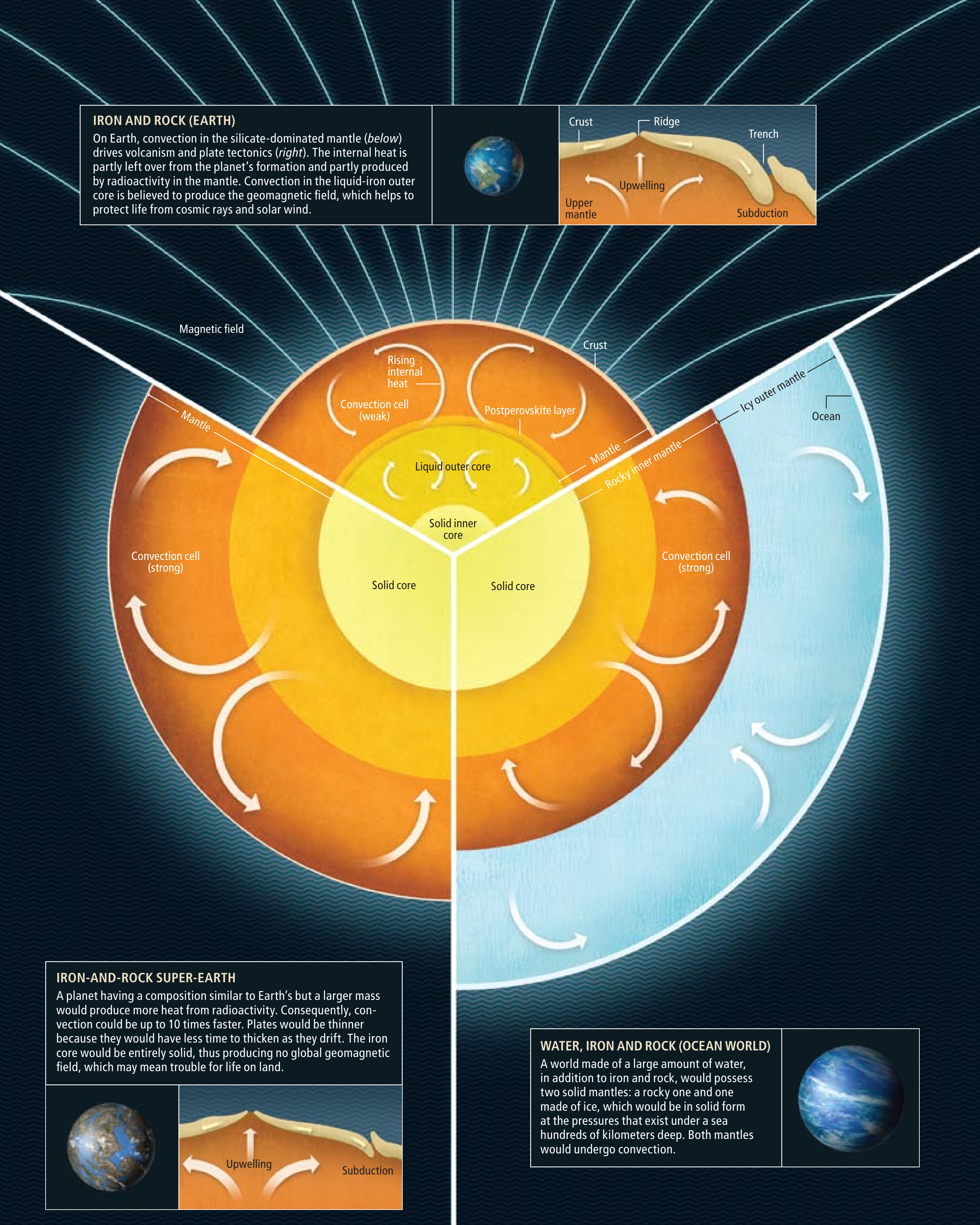
Geophysical activity may be crucial for a planet to be hospitable to life. Theoretical models and computer simulations, together with knowledge about Earth and other planets of the solar system, enable researchers to predict the dynamics of a planet given its mass and composition. Research on super-Earths has focused on two types thought to be common throughout the galaxy, shown here in comparison to Earth. In both cases, convection slowly churns the inner layers (like water in a boiling pot), transporting the planet's internal heat to the surface. This roiling powers volcanism and plate tectonics, helping recycle chemicals into the atmosphere, which in turn can provide nutrients for life and help to stabilize surface temperatures.

▼ THREE ROCKY TYPES

Astronomers have detected more than 80 transiting planets. For those planets, they were able to measure the radius and mass to calculate the mean density, which puts strong constraints on their possible composition. The least dense planets are likely to be gas giants; denser ones may be rocky, with varying amounts of iron and water; even denser ones would likely consist mostly of iron.



PETER AND MARIA HOEY; JEN CHRISTIANSEN (*graph*); RON MILLER (*planets*)



IRON AND ROCK (EARTH)
On Earth, convection in the silicate-dominated mantle (*below*) drives volcanism and plate tectonics (*right*). The internal heat is partly left over from the planet's formation and partly produced by radioactivity in the mantle. Convection in the liquid-iron outer core is believed to produce the geomagnetic field, which helps to protect life from cosmic rays and solar wind.

IRON-AND-ROCK SUPER-EARTH
A planet having a composition similar to Earth's but a larger mass would produce more heat from radioactivity. Consequently, convection could be up to 10 times faster. Plates would be thinner because they would have less time to thicken as they drift. The iron core would be entirely solid, thus producing no global geomagnetic field, which may mean trouble for life on land.

WATER, IRON AND ROCK (OCEAN WORLD)
A world made of a large amount of water, in addition to iron and rock, would possess two solid mantles: a rocky one and one made of ice, which would be in solid form at the pressures that exist under a sea hundreds of kilometers deep. Both mantles would undergo convection.

In some respects, larger, rocky planets could be more likely to harbor life than Earth-size planets.

But at the pressures that exist in a large planet's core, iron can solidify even at temperatures as high as 10,000 kelvins, according to recent theoretical calculations. These high temperatures are probably exceeded only when the planets are very young. But a little cooling would be sufficient for the cores of super-Earths to solidify. Thus, a typical super-Earth may have a completely solid iron core and no global magnetic field. On Earth the field helps to protect us from the noxious effects of solar wind and cosmic rays, especially on land. But we do not know for sure whether it is essential for habitability.

A water-rich planet would develop an even less familiar feature. A thick water layer—a single ocean—would envelop the planet. And something bizarre would happen in the ocean's depths. Water turns into ice when cooled but also when compressed. Thus, on top of the silicate mantle another solid mantle would form, made of white-hot glowing ice. This would not be ordinary ice but rather the crystal structures named ice VII, ice X and ice XI, which so far have been observed only in laboratory experiments.

Whether or not it is rich in water, a super-Earth, being more massive, compresses its interior to unimaginable pressures. A more massive planet will thus be denser than a less massive one of the same composition. In such extreme conditions, hard, rocky materials get even harder than those inside our planet, perhaps harder than diamond. How does Earth-like material behave under these very high pressures? On this front, too, researchers are using theoretical models and experiments to understand super-Earths better.

For example, in recent years scientists have discovered a new structural arrangement, or phase, of material on Earth, called postperovskite [see "The Earth's Missing Ingredient," by Kei Hirose; Scientific American, June]. Although it constitutes only a small portion of Earth's mantle, it would make up most of the mantle of super-Earths. Theory suggests that there could be an even denser phase, but experiments have yet to confirm its existence.

Once we have an idea of the structure of a planet and of what materials make up those layers, we are only half done. The next step is to understand the dynamics of that structure—or lack thereof. In other words, to figure out whether the planet is geologically restless, like Earth, or nearly still and frozen, like Mars.

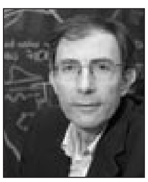
On Earth, mantle convection is the engine of most geologic processes. Below the plates that make up the surface of Earth, the mantle churns as it transports its internal heat toward the surface and then sinks back after it cools, similar to the convection in a boiling pot of water. The heat is in part left over after the planet's formation and in part comes from the decay of radioactive elements in the mantle. We expect rocky super-Earths to have a similar concentration of radioactive heat sources or at least of uranium and thorium, because these elements are uniformly distributed throughout the galaxy and also get easily incorporated into planets during formation. Hence, being bigger than our home planet and having, in absolute terms, more radioactive material, massive Earth analogues produce more internal heat, which would translate into a more vigorous mantle convection.

PRIME REAL ESTATE

THE STRONG STIRRING has several consequences, which ultimately affect the planet's habitability. A perhaps unexpected consequence is that larger planets should have thinner plates. Mantle convection manifests itself on the surface as plate tectonics. Plates move as the mantle churns underneath them. When two plates collide, one of them may slide under the other and then sink back into the mantle, in a process known as subduction. Plates start out very thin at mid-ocean ridges, where they form in part from melted mantle material that rises to the surface, and grow thicker with time as they cool and move toward the subduction zones. According to our models, convection on bigger planets gives rise to larger forces and churns faster. Thus, plates also move faster, so that they have less time to cool and thicken. Being thinner, the plates would be easier to deform, except that the stronger gravity puts more pressure on the faults, which makes them more resistant to sliding. The net effect is that the resistance of the faults is not very different among planets of different size.

That plate tectonics seems easier to sustain on a super-Earth than on a smaller rocky planet is a good thing, because plate tectonics may be good for habitability. On Earth, geologic activity, and volcanism in particular, continually spews carbon dioxide and other gases into the atmosphere. CO_2 reacts with calcium silicate, producing calcium carbonate and silicon dioxide, both of which are solid and eventually end up as sediment on the ocean floors. As oceanic crust subducts back into the mantle, it carries carbon-rich sediment with it. Subduction thus replenishes the mantle with carbon, so that some

[THE AUTHORS]

DIMITAR D. SASSELOV, who was born in Bulgaria, has been professor of astronomy at Harvard University since 1998. He earned a Ph.D. in physics from Sofia University and a Ph.D. in astronomy from the University of Toronto. He studies the evolution and structure of stars and of extrasolar planets and has discovered a few such planets himself. Sasselov is founder and director of the Harvard Origins of Life Initiative, which brings together scientists in the physical and life sciences. DIANA VALENCIA was born in Bogotá, Colombia, and earned a Ph.D. at Harvard University in 2008 with groundbreaking work that combined geophysics and astrophysics to clarify the structure and dynamics of solid planets. She is an Henri Poincaré Postdoctoral Fellow at the Observatoire de la Côte d'Azur in Nice and a recipient of the 2010 NASA Sagan Fellowship.

COURTESY OF JON CHASE *Harvard Press Office* (*Sasselov*); COURTESY OF DIANA VALENCIA (*Valencia*) of it eventually makes its way back into the atmosphere. This so-called carbon-silicate cycle acts as a thermostat to regulate the global surface temperature. On Earth this cycle has helped keep temperatures close to those of liquid water over billions of years. Similarly, plate tectonics recycles other minerals and gases that are important for life, including energy-rich chemicals, such as hydrogen sulfide, that may have fueled life before photosynthesis evolved.

With a super-Earth's more vigorous convection, the timescales of plate production and subduction become shorter, which makes the carbon-silicate cycle faster and more robust. In some respects, then, super-Earths could be even more hospitable to life than Earth-size planets. Moreover, their larger masses would help these planets keep their atmospheres and water from escaping into space. This is an issue particularly for planets that are closer to their stars than, say, Mars is to the sun.

Comparing Earth with the theoretical models of super-Earths of different sizes, we find a rich diversity of stable Earth-like planetary conditions, but this is a family of planets that barely includes Earth. Being smaller, Earth is more vulnerable in many ways. And in our solar system, the smaller planets are geologically rather static. Venus seems marginally capable of moving its plates, but Mars became stagnant early in its history and now does not produce enough emissions to replace its thinning atmosphere. It seems that our planet is barely big enough to have escaped this fate. Still, it is unclear if plate tectonics is really essential for life to exist.

POSTCARD PICTURES

WHAT WOULD the landscapes on a solid super-Earth look like? At first glance they might not seem too different from those on our planet—aside from signs of life, which may or may not be there. Geologic processes would give rise to continents, mountains, oceans and an atmosphere, with clouds and all.

Yet tectonic plates would move up to 10 times faster than on Earth. Mountains would grow and erode at a faster rate, and, because of the stronger gravity, they would not rise as high. (Those mountains would contrast sharply with those of our smaller neighbor Mars, where Olympus Mons is the tallest mountain in the solar system, at 21 kilometers high.) The composition of the atmosphere might also be different because of higher volcanic activity and different rates at which atmospheric gases escape to space.

The era of super-Earth planet exploration has only just begun. We anticipate a rich harvest of super-Earths—hundreds of them—from the Kepler space mission. The next step after Kepler will be to study the atmospheres of those planets and see if we can find any signs of life. To accomplish that we need to determine at least two things—what the planet is made of and what gases are abundant in its atmosphere, which is connected to the dynamics of the interior.

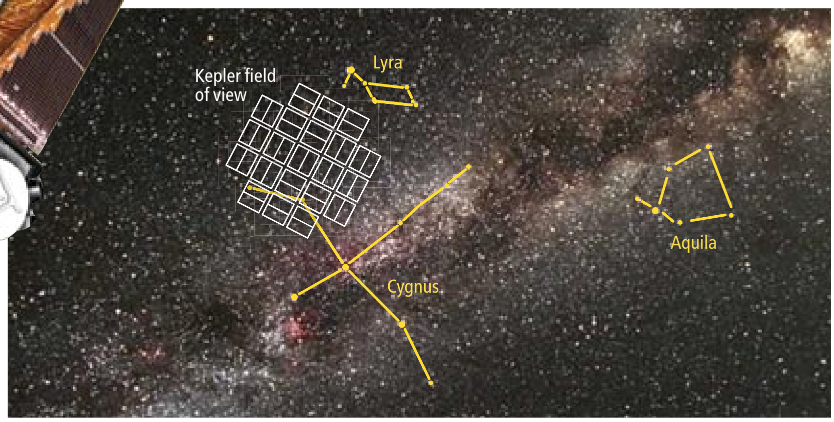
By splitting the light from a planet into its rainbow of colors, scientists will be able to see in it the optical fingerprints of such molecules as water, carbon dioxide and methane. In a few years the successor to the Hubble Space Telescope, called the James Webb Space Telescope, should open its infrared eye and allow glimpses into the atmospheres of super-Earths. The new telescope will need targets to study—some of them will be selected from the best and nearest of the planets discovered by Kepler.

With luck, all-sky ground-based searches and space missions being conceived as follow-ups to Kepler will discover a few transiting super-Earths that are very close to us and thus relatively easy to study. ■

[AN UPCOMING DATA EXPLOSION]

STARING AT 150,000 SUNS

NASA's Kepler space observatory, which went into orbit last year, is dedicated to discovering new planets. Its mission is to continuously stare at more than 150,000 stars in a region of sky near the constellation Cygnus, measuring the stars' brightness to spot planetary transits. The 42 digital sensors in Kepler's camera, each large enough to fit the moon within its field of view, have a total resolution of 95 megapixels and can detect dips in brightness of just one part in 10,000. To help distinguish true signals from noise, Kepler needs to detect putative transits multiple times and thus has to monitor the same stars for years. Kepler has already started discovering new planets, but its best results are expected in a few years.



COURTESY OF NASA KEPLER MISSION (*probe*); COURTESY OF CARTER ROBERTS NASA (*Milky Way*)

MORE TO EXPLORE

Internal Structure of Massive Terrestrial Planets. Diana Valencia, Richard J. O'Connell and Dimitar D. Sasselov in *Icarus*, Vol. 181, No. 2, pages 545–554; April 2006.

Geological Consequences of Super-Sized Earths. Craig O'Neill and Adrian Lenardic in *Geophysical Research Letters*, Vol. 34, L19204; October 11, 2007.

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ORIGINS

WE ARE ALWAYS TELLING STORIES about the world, the universe, ourselves. It helps to make sense of things. But sometimes, through familiarity or neglect, we get lost. We forget where a story really starts, losing sight of where it's headed. What is biodiversity? Are electric cars new? Even the well-worn tale of human origins is missing a key chapter: how a small band of hunter-gatherers survived a climate disaster, becoming ancestors of us all. Here we provide the surprising origins of some strange and familiar things.

BRAD WENNER *Getty Images*

ALL IN THE FAMILY

What persuaded the male hominid to stick around after mating?

FROM THE STANDPOINT of biology, males have nothing to do after copulation. "It's literally wham-bam thank-you-ma'am," says Kermyt G. Anderson, an anthropologist at the University of Oklahoma–Norman and co-author of *Fatherhood: Evolution and Human Paternal Behavior*.

What made the first father stick around afterward? He was needed. At some point in the six million years since the human lineage split from chimpanzees, babies got to be too expensive, in terms of care, for a single mother to raise. A chimp can feed itself at age four, but humans come out of the womb essentially premature and remain dependent on their parents for many years longer. Hunters in Amazonian tribes cannot survive on their own until age 18, according to anthropologist Hillard Kaplan of the University of New Mexico–Albuquerque. Their skills peak in their 30s—not unlike income profiles of modern men and women.

Oddly enough, bird families also tend to have stay-at-home dads. In more than 90 percent of bird species, both parents share the care of their young. This arrangement probably began, at least for most birds, when males started staying around the nests to protect helpless babies from predators. "A flightless bird sitting on a nest is a very vulnerable creature," explains evolutionary biologist Richard O. Prum of Yale University.

Some birds, though, might have inherited their particular form of fatherhood from dinosaurs. Male theropods, a close relative of birds, seem to have done all the nest building, just as male ostriches do today. That doesn't mean everything was on the up and up. A female ostrich will lay an egg in the nest of her mate, but usually a different male fertilizes it. "There's a loose relationship," Prum says, "between paternal care and paternity." *—Brendan Borrell*

CHEESE STORY

Swiss dairy farmers created an American institution

THESE DAYS MOST SWISS CHEESE consumed in the U.S. is made in Ohio, but our palettes—and ham sandwiches—ultimately have that tiny European country to thank. More specifically, the cheese, which only Americans refer to by its generic name, owes much of its success to the Alpine climate and terrain. Swiss cheese is so easy to slice and keeps for such long periods because Swiss farmers of yore had so much trouble selling the product during the brutal winter months.

Hard, mild cheeses similar to the Swiss cheese we know today were first produced in Switzerland and surrounding areas more than 2,000 years ago, according to food historian Andrew Dalby. Because it was difficult for farmers to traverse the mountains in the winters to sell their wares, they may have opted against soft, fresh versions in favor of hard ones, which "securely keep for a good long time," he says.

Those hard Swiss cheeses also had other redeeming characteristics, including a mild, nutty flavor and a useful texture for cooking, which gave them broad appeal. The American Swiss cheese industry got its start in 1845, after 27 Swiss families immigrated to Wisconsin. The characteristic holes—cheese makers call them "eyes"—arise from inconsistent pressing during production and have historically been a sign of imperfection. "You can read medieval or early modern descriptions of cheese making in which you are specifically instructed to avoid this," Dalby says. But now "it has become almost a trademark." *—Melinda Wenner Moyer*

ELECTRONIC PATHOGENS

The first computer virus spawned an arms race in software

MALWARE, THE MENAGERIE of malicious software that includes Trojan horses and worms, first made its appearance in the early 1970s, before personal computers had entered the public consciousness. A self-replicating program called Creeper infected the ARPANET, the forerunner of the Internet. This virus was not malicious—it simply printed on a screen, "I'm the creeper, catch me if you can!"—but it triggered the first antivirus program, Reaper, which removed it.

Viruses went public in a big way with the proliferation of the personal computer during the 1980s. The first PC virus, Elk Cloner, infected early Apple computers. In 1986 a virus called Brain emerged on PCs that booted up with Microsoft's disk operating system, spreading via floppy disks. *—Mike May*

ROSEMARY CALVERT *Getty Images (cheese)*; CATHY CRAWFORD *Getty Images (computer keys)*

BEFORE MICKEY MOUSE

The inspiration for today's animated pictures began long ago with dreams and toys

EACH TIME A PHOTON hits light receptors on the retina, it triggers a Rube-Goldbergian chemical reaction that takes tens of milliseconds to reset. We don't notice this interruption—our brains smooth it over into an apparently fluid stream of visual information—but the delay provided just the opening animators like Walt Disney needed.

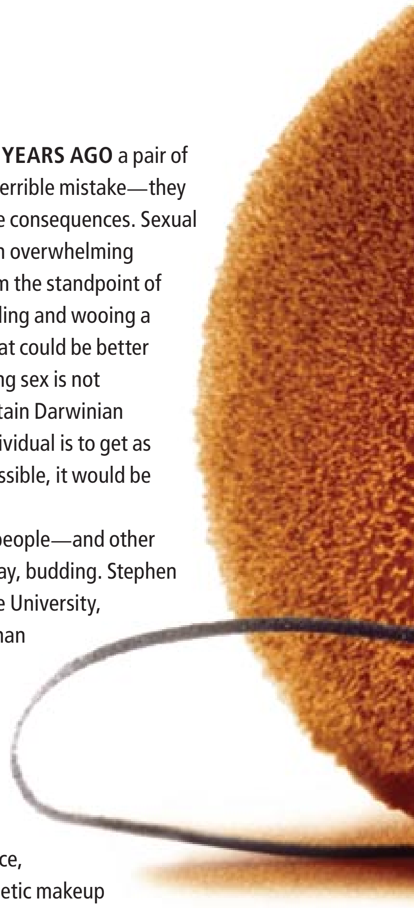
Animators, of course, were not the first to notice this perceptual quirk, often called persistence of vision. Aristotle found that when he stared at the sun, the burned-in image faded away slowly. Roman poet Titus Lucretius Carus described a dream in which a sequence of images presented rapidly before him produced the illusion of motion. By then the Chinese had invented the *chao hua chih kuan* ("the pipe that makes fantasies appear"), a cylindrical contraption that, when spun in the wind, displayed a succession of images. It gave "an impression of movement of animals or men," writes Joseph Needham in *Science and Civilisation in China.*

In the 19th century Europeans developed their own animated pictures in the form of spinning disks and zoetropes featuring sequential drawings visible through a slit, says Donald Crafton of the University of Notre Dame and author of *Before Mickey.* The first animated film, *Phantasmagoria,* came out in 1908, depicting the decapitation of a clown and other slapstick in a series of 700 drawings, which took two minutes to show. It was a visual tour de force, though choppy by today's exacting standards.

Science didn't catch up to the animators until 1912, when Max Wertheimer, in *Experimental Studies on the Seeing of Motion,* revealed that it takes 25 frames per second to fool the human eye. It's a good thing people don't have the vision of fruit flies, which need more than 200 frames per second to succumb to the illusion of motion. *—Brendan Borrell*

IS SEX REALLY NECESSARY?

Most living things do it, but nobody knows why



APPROXIMATELY TWO BILLION YEARS AGO a pair of single-celled organisms made a terrible mistake—they had sex. We're still living with the consequences. Sexual reproduction is the preferred method for an overwhelming portion of the planet's species, and yet from the standpoint of evolution it leaves much to be desired. Finding and wooing a prospective mate takes time and energy that could be better spent directly on one's offspring. And having sex is not necessarily the best way for a species to attain Darwinian fitness. If the evolutionary goal of each individual is to get as many genes into the next generation as possible, it would be simpler and easier to just make a clone.

The truth is, nobody really knows why people—and other animals, plants and fungi—prefer sex to, say, budding. Stephen C. Stearns, an evolutionary biologist at Yale University, says scientists now actively discuss more than 40 different theories on why sex is so popular. Each has its shortcomings, but the current front-runner seems to be the Red Queen hypothesis. It gets its name from a race in Lewis Carroll's *Through the Looking Glass.* Just as Alice has to keep running to stay in the same place, organisms have to keep changing their genetic makeup to stay one step ahead of parasites. Sexual reproduction allows them to shuffle their genetic deck with each generation.

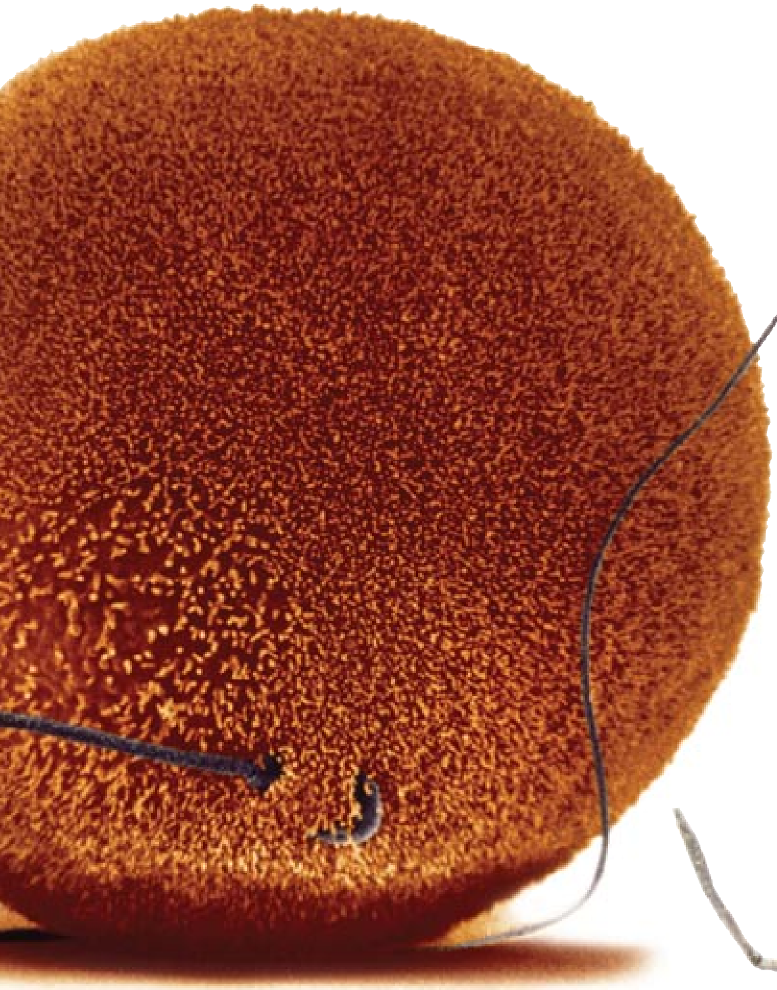
That's not to say that sex is forever. When it comes to reproduction, evolution is a two-way street. When resources and mates are scarce, almost all types of animals have been known to revert to reproducing asexually. In May 2006 Flora, a Komodo dragon living in an English zoo, laid 11 eggs,

ON THE PARASITE'S TRAIL

Scientists have traced malaria to its first human victims a mere 10,000 years ago

FOR MORE THAN A CENTURY researchers have been trying to figure out how malaria first arose in humans. The question is urgent, because more than two million people die every year from *Plasmodium,* the malaria parasite, and understanding its origins might one day lend clues to its complex biology. A piece of the puzzle fell into place in September 2009, when a team of researchers discovered that the main strain

GETTY IMAGES (*zoetrope*); EADWEARD MUYBRIDGE *Getty Images* (*film strip*); FRANK GREENAWAY *Getty Images* (*mosquito*)



even though she had had no contact with males. Virgin births are the norm for the flower-pot snake, a female-only creature that has spread throughout the world, one individual at a time. Mammals, including humans, appear to have been denied the cloning option, however. Our lives seem fated to include plenty of sex, in good times and in bad. *—Brendan Borrell*

that infects human beings—*P. falciparum*—evolved from another version of the parasite, *P. reichenowi,* which currently infects chimpanzees. And it happened a mere 10,000 years ago—a moment in evolutionary terms.

The finding rests on a molecular comparison of the genomes of the two parasites. Stephen Rich, an evolutionary geneticist at the University of Massachusetts Amherst, and his colleagues measured the diversity of the genomes, a rough proxy for age (genomes tend to acquire genetic components over time). *Reichenowi*'s genome can be 20 times more diverse than *falciparum*'s, which means *reichenowi* is much older. "It seems that malaria has been in chimps as long as they've been chimps," Rich says.

Following the trail back to the origin of *reichenowi* is a more complicated problem, not least because malaria is so widespread. "In terrestrial vertebrates, we find it virtually everywhere we look," Rich observes. "We're only getting started." *—Mike May*

SNAP, CRACKLE, BANG

The ancient Chinese invented fireworks to scare off 10-foot-tall mountain men

THAT RAUCOUS RITE OF SUMMER—the fireworks display—may have started as a scholarly tradition in ancient China. Before the Chinese got around to inventing paper in the second century A.D., scribes, using a stylus, would etch ideograms on the rounded surface of green bamboo stalks. The medium served as a way for recording transactions and stories. As the stalks dried over the fire, air pockets in the wood would often burst with a loud cracking noise.

The noise, of course, gradually became the whole point of the exercise. The classic *I Ching,* or *Book of Changes,* explains how the cracks and pops succeeded in scaring off the Shan Shan, 10-foot-tall mountain men. Later, the Chinese spiced things up by adding gunpowder to the stalks.

The first fireworks display didn't take place until the 12th century rolled around. In 1267 English philosopher Roger Bacon wrote about "that toy of children" and the "horrible sound" it produces, which "exceeds the roar of sharp thunder." Those sharp bangs evoke nothing more than, yes, another Fourth of July celebration. *—Mike May*

DAVID M. PHILLIPS *Photo Researchers, Inc.* (*sperm and egg*); GETTY IMAGES (*firecrackers*)

THORNY FENCE

The invention of barbed wire was a huge commercial success—and the subject of furious legal battles

AT SOME POINT IN THE HISTORY of civilization, shepherding gave way to farming. That created a need for some way of keeping cows and pigs from wandering freely through the meadows. The fence was born. Wooden fences were among the earliest, but they are expensive and time-consuming to build. By 1870 smooth cable was easy to get hold of and came into wide use on ranches. Cattle would rub their back on the wire, and sometimes one would slip through. Eventually the herds caught on.

That got Michael Kelly, an inventor from New York City, wondering how he might make the wire less comfortable as a bovine back scratcher. He got the idea to twist bits of sharp pointed wire onto ordinary cable, and in 1868 he patented his "thorny fence." It was a big success—and a magnet for lawsuits. "Almost overnight it developed into a source of wealth and furious litigation colored by impassioned charges and countercharges of patent infringement and greed," says historian Robert T. Clifton.

Joseph Glidden of DeKalb, Ill., also hit legal snags over an improved wire that used two strands to lock the barbs in place. In 1892 his case went before the U.S. Supreme Court, which ruled in his favor, making him the undisputed father of an invention that more than any other marked the closing of the West's open range. —*Mike May*

SCRUBS

A rise in maternity ward deaths led one physician to discover the importance of hand washing

IN THE MID-1840S Hungarian physician Ignaz Semmelweis saw with alarm that 15 percent of new mothers in his Vienna General Hospital were dying of an illness called puerperal fever. Semmelweis was desperate to prevent the illnesses, but he didn't know how. As he pondered the problem, he learned that his friend, forensic pathologist Jakob Kolletschka, had died from what sounded like the same illness. It happened only a few days after a student accidentally pricked Kolletschka with a scalpel that had been used to dissect a cadaver.

The news gave Semmelweis pause. Medical students at his hospital would routinely go right from the morgue to the maternity ward without ever washing their hands. Were they carrying an infection to the mothers? Was that why they were dying? Could hand washing help?

To test his dirty-hands hypothesis, Semmelweis made his students wash their hands in a mixture of water and chlorine (soap and water did not eliminate the cadaver smell). Fevers in the maternity ward quickly dropped by 10 percent. Hand washing became standard procedure at Semmelweis's hospital.

It took 40 years for the policy to take hold widely. Even today hospital workers don't follow it as consistently as they should. According to an ongoing study from the Maryland Health Quality and Cost Council, 90 percent of staff wash their hands when someone is looking, but only 40 percent do when alone. —*Mike May*

STEVEN PUETZER *Getty Images (hand washing)*; GETTY IMAGES *(barbed wire)*

MORAL ANIMAL

A sense of right and wrong starts with innate brain circuitry

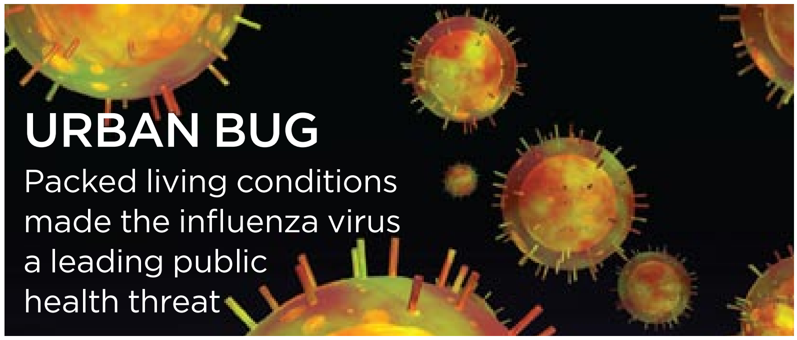
THE ROOTS OF MODERN MORALITY have long been a point of contention among psychologists, philosophers and neuroscientists. Do our ethical foundations arise from our relatively recent ability to reason or from our ancient emotions? Studies have recently lent support to the notion that we owe much of our sense of right and wrong to our animal ancestors.

Evidence that morality comes before reason is supported by primate studies. A chimpanzee, for instance, will sometimes drown to save its peers and refuse food if doing so prevents others from injury. That's not to say they are morally sophisticated beings, but "it's not as if morality and our moral rules are just a pure invention of the religious or philosophical mind," explains Frans de Waal, a primatologist and psychologist at Emory University. De Waal's work suggests that our morality is an outgrowth of our ancestors' social tendencies, an indication that it is at least in part an evolved trait (an idea Charles Darwin shared). Dogs, too, seem to have a keen sense of "wild justice," says Marc Bekoff, a professor emeritus at the University of Colorado at Boulder. He has observed a sense of morality among dogs at play. "Animals know right from wrong," he notes.

If morality is innate rather than learned, then it should have left biological traces. Studies suggest that moral decisions involve certain parts of the brain associated with prosocial tendencies and emotional regulation, such as the ventromedial prefrontal cortex. In brain scans, this region lights up when subjects choose to donate money to charity, and those with damage to this region make unexpected moral judgments. Some ethical dilemmas also activate brain regions involved in rational decision making, such as one called the anterior cingulate cortex—a finding that implies that higher-order brain functions may also contribute to our morality, even if it's rooted in emotions.

Ultimately, de Waal says, we need to thank our evolutionary ancestors for far more than just bestial urges. "When humans kill each other or commit genocide, we say we're acting like animals," he says. But "you can see the same sort of thing with regard to our positive behavior."

—Melinda Wenner Moyer



URBAN BUG

Packed living conditions made the influenza virus a leading public health threat

HIPPOCRATES DESCRIBED THE SYMPTOMS of the flu some 2,400 years ago. But the influenza virus didn't become a true menace until the rise of stable, densely populated settlements and the growth of animal husbandry. This crowding of people and their animals furnished the virus with ample opportunities to jump from one species to another, acquiring deadly attributes along the way.

The first influenza pandemics were recorded during the 1500s. The one that occurred in 1580 traced a path that epidemiologists today would recognize: it began in Asia during the summer and then spread to Africa, Europe and America over the next six months. Another big epidemic hit in 1789, the year that George Washington took office, "before modern means of rapid travel were available and when a man could go no faster than his horse could gallop," wrote virologist and epidemiologist Richard E. Shope in 1958. Even so, he said, it "spread like wildfire."

Shope knew influenza well: in 1931 he became the first scientist to transmit the virus between two animals, by transferring mucus from one pig's nose to another's. Because Shope had filtered bacteria from the mucus beforehand, his experiment suggested, for the first time, that the flu was caused by a virus. Two years later a group of U.K. scientists became the first to isolate a human form of the virus, from a sick ferret. *—Melinda Wenner Moyer*

FORMER LIFE OF THE ELECTRIC CAR

A century ago taxicabs had batteries, not gas guzzlers, under their hoods

IN WHAT MAY HAVE BEEN THE FIRST attempt at an electric car, Scottish inventor Robert Anderson built a "crude electric carriage" in the mid- to late 1830s. It didn't get far. For one thing, its battery wasn't good enough. (Today's green car engineers can sympathize.) It also faced stiff competition from steam-powered cars.

When rechargable batteries started to appear in the mid-1800s, electric vehicles got a fillip. In 1897 the Electric Carriage and Wagon Company in Philadelphia assembled a fleet of electric-powered taxis for New York City. By 1902 the Pope Manufacturing Company in Hartford, Conn., had built around 900 electric vehicles, most of which were used as cabs. That same year Studebaker, which had gotten its start in horse-drawn wagons, entered the car market in Indiana with an electric model. Through the early 1900s electric vehicles ran smoother and quieter than their gas-guzzling, internal-combustion-engine-powered rivals.

Where the electric car stumbled was range—it couldn't go far between rechargings. By 1920 gas-powered rivals emerged as the clear winner, a twist of history that engineers are now working furiously to undo. *—Mike May*

ALFRED PASIEKA *Photo Researchers, Inc. (flu virus)*; CORBIS BETTMANN *(carriage)*

THE FIRST HUMVEE

Wheeled vehicles may have first arisen as a tool of war

SIR C. LEONARD WOOLLEY'S 1922 excavation of the Royal Cemetery of Ur—a Sumerian site located in modern-day Iraq—was, by early 20th-century standards, a major media event. Thomas Edward Lawrence, a.k.a. Lawrence of Arabia, who had achieved fame for his dashing exploits during the Arab Revolt several years earlier, helped to organize the expedition. British mystery writer Agatha Christie paid a visit to the site and penned *Murder in Mesopotamia* as a tribute (she would later marry Woolley's assistant). All this fuss over a box with a picture of a wheel on it.

It wasn't just any box, of course. It was the Standard of Ur, a 4,600-year-old container, the size of a shoebox (*above*), encrusted in lapis lazuli. Most important, it featured an illustration of ancient warfare that included the oldest uncontested image of the wheel in transportation. A series of images depicted tanklike carriages, each with four solid wheels braced to their axles and a team of horses propelling them forward. The wheeled carriages clearly provided soldiers with better protection against ambush than the poor foot soldiers had, who are shown squirming to avoid horses' hooves.

This ancient Humvee wasn't the only way fifth-millennium engineers deployed wheels. The Sumerians, Egyptians and Chinese all used wheels for spinning pots, and Egyptians moved massive stones with log rollers. Wheels never caught on for ordinary transport because they weren't useful on the sandy soils of the world's trade routes, says Richard Olson, a historian and author. Camels remained the all-terrain vehicle of choice for another 2,000 years or so.

Wheeled vehicles didn't take off until the advent of roads. The Egyptians built extensive dirt roads and paved some of them with sandstone, limestone and even a surfacing of petrified wood. By as far back as 3,500 years ago, they fashioned a metal wheel with six spokes, and from the Middle East to Russia, agile, two-wheeled chariots became all the rage. *—Brendan Borrell*

GRAVITY'S TUG

The first black holes are almost as old as the universe itself

THE IDEA THAT A BLACK HOLE could possibly exist came from an English rector, John Michell. In 1783 he calculated that the force of gravity exerted by a massive star could prevent light from escaping its surface. Michell's work was largely forgotten for 200 years. In 1971 astrophysicists noticed flickering x-rays coming from the constellation Cygnus, 6,000 light-years away: the radiation indicated that a black hole was apparently circling a star. As with any black hole, it formed as a star ran out of fuel and collapsed in on itself. If the sun were to somehow become a black hole, it would be less than three miles across, trapping light in the warped space that enfolds it. For Earth to become a black hole, it would be the size of a marble.

The first black holes in the universe arose nearly 14 billion years ago, contends Abraham Loeb, an astrophysicist at Harvard University. At that time, gas began to condense into clouds that fragmented into massive stars 100 times the size of the sun, which in turn collapsed into black holes. Fortunately, the spinning of early galaxies limited the growth of the black holes at their cores, allowing stars to form.

Physicists have now begun to make something akin to black holes on Earth. Chinese researchers built concentric cylinders that mimic a black hole, bending microwave radiation in on itself as it passes from outer to inner surfaces. And a real black hole could still improbably pop out of the Large Hadron Collider near Geneva. *—Brendan Borrell*

RAINBOW CELLS

Biodiversity was the first step toward complex life

Witnesses were absent for the comings and goings of the first life some four billion years ago, but scientists are pretty sure the typical Earth creature in those days consisted of no more than a single cell. That doesn't mean the planet was a dull sea of sameness. Single-celled creatures may have acquired genetic diversity early on.

Here's why. When cells divide, mistakes have a way of creeping into genetic material. Variants that enhance a cell's ability to survive and reproduce become more common over successive generations. This basic fact of evolution applied to the early Earth. "Variation is necessary for there to be evolution by natural selection in the first place," explains Andrew Hamilton, a philosopher of science at Arizona State University. "Biodiversity originated at the point that there was variation on which selection could operate."

Today we think of biodiversity in terms of multicellular life, but flowering plants and animals didn't arrive until relatively recently (540 million years ago). Although some evidence suggests that having a wide variety of species makes an ecosystem more stable, the jury is still out. It is of no comfort to know that the worst catastrophe would still preserve some biodiversity—even if only for the lowly cell. —*Melinda Wenner Moyer*

ZERO

How nothing became something

NOBODY KNEW HOW MUCH we needed nothing until we had a number for it. Without zero, negative and imaginary numbers would have no meaning, and it would be impossible to solve quadratic equations, a mainstay of applied math. Without zero to act as a placeholder to distinguish, say, 10 from 100, all but the simplest arithmetic requires an abacus or counting board. "If we didn't have zero, our system of numbers would be incomplete," says Charles Seife, author of *Zero: The Biography of a Dangerous Idea.* "It would really break down without zero."

Zero arrived on the scene in two installments. Around 300 B.C., Babylonians developed a proto-zero—two slanted wedges pressed into clay tablets—that served as a placeholder in their funky sexagesimal, or base 60, number system. By the fifth century, the concept of zero migrated to India and made its symbolic entrance as a dot carved on a wall at the Chaturbhuja Temple in Gwalior. Then, like a pebble dropped into a puddle, the symbol for zero expanded to an "0" and became a number with properties all its own: an even number that is the average of –1 and 1. In 628 mathematician Brahmagupta pontificated on the frightening properties of zero: multiply anything by zero, and it, too, turns to nothing. Independently, Mayans in the Americas developed their own zero to assist in the study of astronomy.

Over time the expansion of the Islamic empire spread the Indian zero back to the Middle East and, eventually, to the Moors in Spain, where it became one of 10 Arabic numerals, as we refer to them today. European scholars clung to their Roman numerals. Zero's official endorsement by the Western world came by way of Italian mathematician Fibonacci (Leonardo of Pisa), who included it in a textbook in 1202.

—*Brendan Borrell*

NOODLING THE NOODLES

It took thousands of years to go from mush to spaghetti

FOOD HISTORIAN FRANCINE SEGAN asserts that pasta emerged more than 5,000 years ago when an enterprising chef happened upon the now seemingly obvious idea of mushing flour and water together to create something that looked surprisingly like lasagna. "It breaks my heart to tell you this," says Segan, invoking her own Italian heritage, "but the first to make those noodles might have been the ancient Greeks. Lots of references in ancient Greek writing—even in 3,000 B.C.—talk about layers that sound a lot like lasagna."

Spaghetti took longer but appears to have taken shape in Italy. A popular misconception has Marco Polo introducing Italians to pasta when he returned from China in 1295, but Italy already had pasta by then. "In Sicily there is a town called Trabia," wrote Arab geographer Muhammad al-Idrisi in 1154. "In this town they made a food of flour in the form of strings." He describes a true pasta industry: foodstuffs were first dried in the sun and then shipped by boat to other regions of Italy and even other countries.

A few hundred years later Leonardo da Vinci invented a machine that turned dough into edible strings. Technical glitches kept his pasta maker from achieving the mechanization of the industry he had hoped for. Still, the Italians succeeded in refining the art of pasta making, crafting more elaborate forms of mushed dough than anyone else.

—*Mike May*

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Cave today known simply as PP13B, near Mossel Bay, South Africa, sheltered humans between 164,000 and 35,000 years ago, at a time when *Homo sapiens* was in danger of dying out. These people may have been the ancestors of us all.

When the Sea Saved Humanity

Shortly after *Homo sapiens* arose, harsh climate conditions nearly extinguished our species. Recent finds suggest that the small population that gave rise to all humans alive today survived by exploiting a unique combination of resources along the southern coast of Africa

BY CURTIS W. MAREAN

WITH THE GLOBAL POPULATION of humans currently approaching seven billion, it is difficult to imagine that *Homo sapiens* was once an endangered species. Yet studies of the DNA of modern-day people indicate that, once upon a time, our ancestors did in fact undergo a dramatic population decline. Although scientists lack a precise timeline for the origin and near extinction of our species, we can surmise from the fossil record that our forebears arose throughout Africa shortly before 195,000 years ago. Back then the climate was mild and food was plentiful; life was good. But around 195,000 years ago, conditions began to deteriorate. The planet entered a long glacial stage known as Marine Isotope Stage 6 (MIS6) that lasted until roughly 123,000 years ago.

A detailed record of Africa's environmental conditions during glacial stage 6 does not exist, but based on more recent, better-known glacial stages, climatologists surmise that it was almost certainly cool and arid and that its deserts were probably significantly expanded relative to their modern extents. Much of the landmass would have been uninhabitable. While the planet was in the grip of this icy regime, the number of people plummeted perilously—from more than 10,000 breeding individuals to just hundreds. Estimates of exactly when this bottleneck occurred and how small the population became vary among genetic studies, but all of them indicate that everyone alive today is descended from a small population that lived in one region of Africa sometime during this global cooling phase.

I began my career as an archaeologist working in East Africa and studying the origin of modern humans. But my interests began to shift when I learned of the population bottleneck that geneticists had started talking about in the early 1990s. Humans today exhibit very low genetic diversity relative to many other species with much smaller population sizes and geographic ranges—a phenomenon best explained by the occurrence of a population crash in early *H. sapiens*. Where, I wondered, did our ancestors manage to survive during the climate catastrophe? Only a handful of regions could have had the natural resources to support hunter-gatherers. Paleoanthropologists argue vociferously over which of these areas was the ideal spot. The southern coast of Africa, rich in shellfish and edible plants year-round, seemed to me as if it would have been a particularly good refuge in tough times. So, in 1991, I decided I would go there and look for sites with remains dating to glacial stage 6.

KEY CONCEPTS

- At some point between 195,000 and 123,000 years ago, the population size of *Homo sapiens* plummeted, thanks to cold, dry climate conditions that left much of our ancestors' African homeland uninhabitable. Everyone alive today is descended from a group of people from a single region who survived this catastrophe.
- The southern coast of Africa would have been one of the few spots where humans could survive during this climate crisis, because it harbors an abundance of shellfish and edible plants.
- Excavations of a series of sites in this region have recovered items left behind by what may have been that progenitor population.
- The discoveries confirm the idea that advanced cognitive abilities evolved earlier than previously thought—and may have played a key role in the survival of the species during tough times.

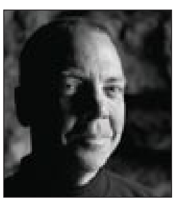
—The Editors

PER-ANDERS PETTERSON

SEASIDE SANCTUARY

Between 195,000 and 123,000 years ago, the planet was locked in an ice age known as Marine Isotope Stage 6, rendering much of the African continent cool and arid—unsuitable for the plants and animals that *Homo sapiens* ate. Only a few regions could have supported our species, namely, those with grassland or Mediterranean scrub vegetation. The southern coast would have been a particularly plentiful oasis, thanks to the edible fynbos plants that grow only here and the dense shellfish beds nurtured by the Agulhas current and the Benguela upwelling of nutrient-rich cold water from the sea bottom.

[THE AUTHOR]



CURTIS W. MAREAN is a professor at the School of Human Evolution and Social Change at Arizona State University and a member of the Institute of Human Origins. He studies the origins of modern humans, the prehistory of Africa, paleoclimates and paleoenvironments, and animal bones from archaeological sites. Marean is particularly interested in human occupation of coastal ecosystems. He is the principal investigator for the South African Coast Paleoclimate, Paleoenvironment, Paleoecology, Paleoanthropology (SACP4) project, funded by the National Science Foundation.

My search within that coastal area was not random. I had to find a shelter close enough to the ancient coastline to provide easy access to shellfish and elevated enough that its archaeological deposits would not have been washed away 123,000 years ago when the climate warmed and sea levels surged. In 1999 my South African colleague Peter Nilssen and I decided to investigate some caves he had spotted at a place called Pinnacle Point, a promontory near the town of Mossel Bay that juts into the Indian Ocean. Scrambling down the sheer cliff face, we came across a cave that looked particularly promising—one known simply as PP13B. Erosion of the sedimentary deposits located near the mouth of the cave had exposed clear layers of archaeological remains, including hearths and stone tools. Even better, a sand dune and a layer of stalagmite capped these remnants of human activity, suggesting that they were quite old. By all appearances, we had hit the jackpot. The following year, after a local ostrich farmer built us a 180-step wooden staircase to allow safer access to the site, we began to dig.

Since then, my team's excavations at PP13B and other nearby sites have recovered a remarkable record of the activities undertaken by the people who inhabited this area between approximately 164,000 and 35,000 years ago, hence during the bottleneck and after the population began to recover. The deposits in these caves, combined with analyses of the ancient environment there, have enabled us to piece together a plausible account of how the prehistoric residents of Pinnacle Point eked out a living during a grim climate crisis. The remains also debunk the abiding notion that cognitive modernity evolved long after anatomical modernity: evidence of behavioral sophistication abounds in even the oldest archaeological levels at PP13B. This advanced intellect no

PER-ANDERS PETTERSON (*Marean*); DON FOLEY (*map*); LUCY READING-IKKANDA (*globe*)

HIGH AND DRY

Finding archaeological sites dating to glacial stage 6 required searching for shelters that were close enough to the sea to allow relatively easy access to shellfish yet elevated enough that their ancient remains would not have washed away when the sea level rose 123,000 years ago. PP13B and other caves carved into the sheer cliff face of a promontory called Pinnacle Point meet those requirements and have yielded a plethora of remains dating to this critical juncture in human prehistory.

PER-ANDERS PETTERSON

doubt contributed significantly to the survival of the species, enabling our forebears to take advantage of the resources available on the coast.

While elsewhere on the continent populations of *H. sapiens* died out as cold and drought claimed the animals and plants they hunted and gathered, the lucky denizens of Pinnacle Point were feasting on the seafood and carbohydrate-rich plants that proliferated there despite the hostile climate. As glacial stage 6 cycled through its relatively warmer and colder phases, the seas rose and fell, and the ancient coastline advanced and retreated. But so long as people tracked the shore, they had access to an enviable bounty.

A COASTAL CORNUCOPIA

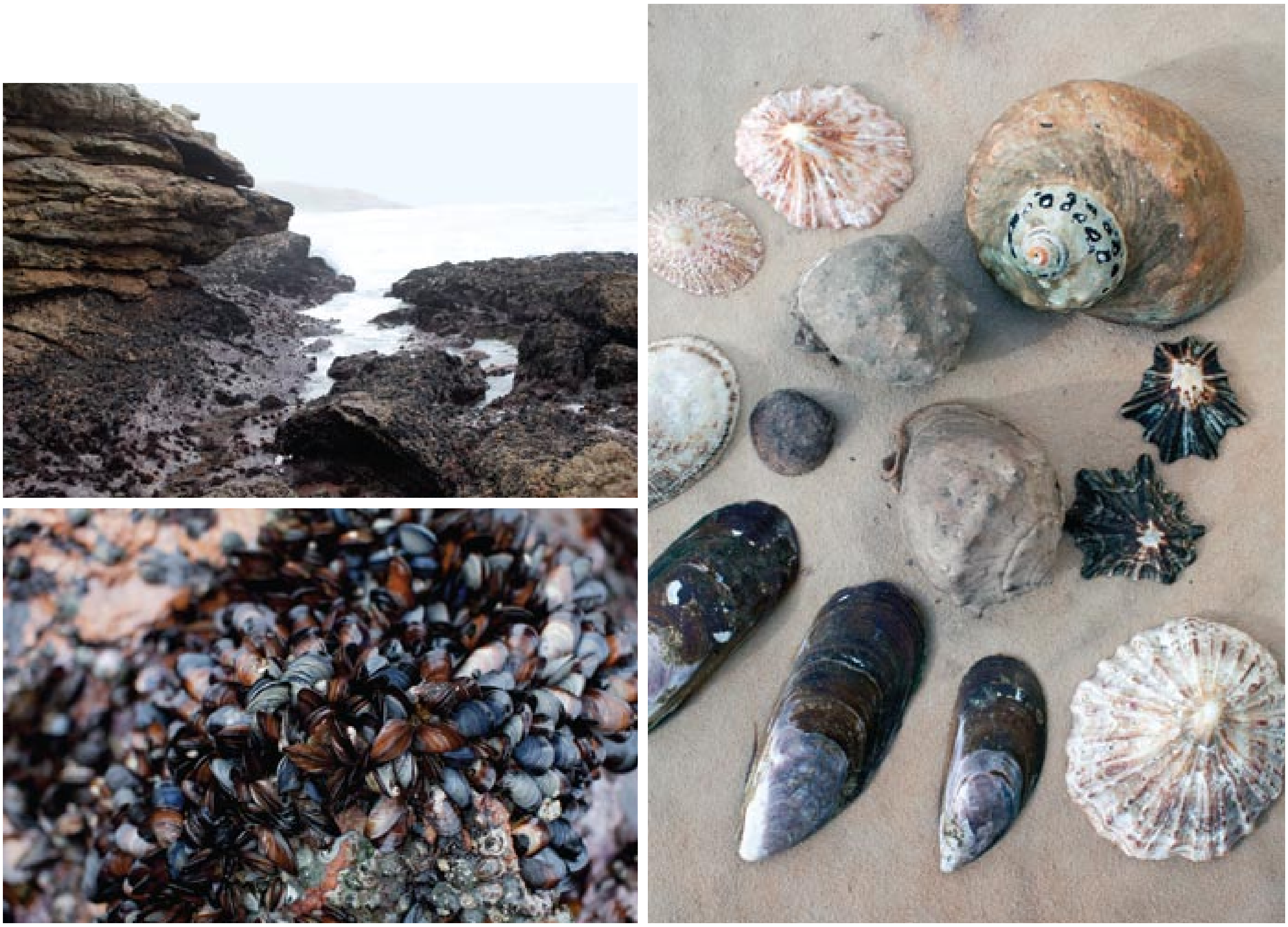
FROM A SURVIVAL STANDPOINT, what makes the southern edge of Africa attractive is its unique combination of plants and animals. There a thin strip of land containing the highest diversity of flora for its size in the world hugs the shoreline. Known as the Cape Floral Region, this 90,000-square-kilometer strip contains an astonishing 9,000 plant species, some 64 percent of which live only there. Indeed, the famous Table Mountain that rises above Cape Town in the heart of the Cape Floral Region has more species of plants than does the entire U.K. Of the vegetation groups that occur in this realm, the two most extensive are the fynbos and the renosterveld, which consist largely of shrubs. To a human forager equipped with a digging stick, they offer a valuable commodity: the plants in these groups produce the world's greatest diversity of geophytes—underground energy-storage organs such as tubers, bulbs and corms.

Geophytes are an important food source for modern-day hunter-gatherers for several reasons. They contain high amounts of carbohydrate; they attain their peak carbohydrate content reliably at certain times of year; and, unlike aboveground fruits, nuts and seeds, they have few predators. The bulbs and corms that dominate the Cape Floral Region are additionally appealing because in contrast to the many geophytes that are highly fibrous, they are low in fiber relative to the amount of energy-rich carbohydrate they contain, making them more easily digested by children. (Cooking further enhances their digestibility.) And because geophytes are adaptations to dry conditions, they would have been readily available during arid glacial phases.

The southern coast also has an excellent source of protein to offer, despite not being a prime hunting ground for large mammals. Just offshore, the collision of nutrient-rich cold waters from the Benguela upwelling and the warm Agulhas current creates a mix of cold and warm eddies along the southern coast. This varied ocean environment nurtures diverse and dense beds of shellfish in the rocky intertidal zones and sandy beaches. Shellfish are a very high quality source of protein and omega-3 fatty acids. And as with geophytes, glacial cooling does not depress their numbers. Rather, lower ocean temperatures result in a greater abundance of shellfish.

SURVIVAL SKILLS

WITH ITS COMBINATION of calorically dense, nutrient-rich protein from the shellfish and low-fiber, energy-laden carbs from the geophytes, the southern coast would have provided an ideal diet for early modern humans during glacial stage 6. Furthermore, women could obtain both these



GONE SHELLFISHING

Shellfish, which are rich in protein, are thought to have aided survival of the Pinnacle Point population because they abound year-round in the rocky intertidal zone along the southern coast of Africa (*upper left*). Brown mussels (*lower left*) have turned up in even the earliest levels of PP13B, dating to 164,000 years ago, revealing that humans began exploiting marine resources earlier than previously thought. In addition to mussels, the occupants of the Pinnacle Point sites collected various kinds of limpets as well as sea snails called alikreukel for food and gathered empty shells of helmet snails for their aesthetic appeal (*right*).

PER-ANDERS PETTERSON

resources on their own, freeing them from relying on men to provision them and their children with high-quality food. We have yet to unearth proof that the occupants of PP13B were eating geophytes—sites this old rarely preserve organic remains—although younger sites in the area contain extensive evidence of geophyte consumption. But we have found clear evidence that they were dining on shellfish. Studies of the shells found at the site conducted by Antonieta Jerardino of the University of Barcelona show that people were gathering brown mussels and local sea snails called alikreukel from the seashore. They also ate marine mammals such as seals and whales on occasion.

Previously the oldest known examples of humans systematically using marine resources dated to less than 120,000 years ago. But dating analyses performed by Miryam Bar-Matthews of the Geological Survey of Israel and Zenobia Jacobs of University of Wollongong in Australia have revealed that the PP13B people lived off the sea far earlier than that: as we reported in 2007 in the journal *Nature*, marine foraging there dates back to a stunning 164,000 years ago. By 110,000 years ago the menu had expanded to include species such as limpets and sand mussels.

This kind of foraging is harder than it might seem. The mussels, limpets and sea snails live on the rocks in the treacherous intertidal zone, where an incoming swell could easily knock over a hapless collector. Along the southern coast, safe harvesting with sufficiently high returns is only possible during low spring tides, when the sun and moon align, exerting their maximum gravitational force on the ebb and flow of the water. Because the tides are linked to the phases of the moon, advancing by 50 minutes a day, I surmise that the people who lived at PP13B—which 164,000 years ago was located much farther inland, two to five kilometers from the water, because of lower sea levels—scheduled their trips to the shore using a lunar calendar of sorts, just as modern coastal people have done for ages.

Harvesting shellfish is not the only advanced behavior in evidence at Pinnacle Point as early as 164,000 years ago. Among the stone tools are significant numbers of "bladelets"—tiny flakes twice as long as they are wide—that are too small to wield by hand. Instead they must have been attached to shafts of wood and used as projectile weapons. Composite toolmaking is indicative of considerable technological know-how, and the bladelets at PP13B are among the oldest examples of it. But we soon learned that these tiny implements were even more complex than we thought.

Most of the stone tools found at coastal South African archaeological sites are made from a type of stone called quartzite. This coarse-grained rock is great for making large flakes, but it is difficult to shape into small, refined tools. To manufacture the bladelets, people used fine-grained rock called silcrete. There was something odd about the archaeological silcrete, though, as observed by Kyle S. Brown of the Institute of Human Origins at Arizona State University, an expert stone tool flaker on my team. After years of collecting silcrete from all over the coast, Brown determined that in its raw form the rock never has the lustrous red and gray coloring seen in the silcrete implements at Pinnacle Point and elsewhere. Furthermore, the raw silcrete is virtually impossible to shape into bladelets. Where, we wondered, did the toolmakers find their superior silcrete?

A possible answer to this question came from Pinnacle Point Cave 5-6, where one day in 2008 we found a large piece of silcrete embedded in ash. It had the same color and luster seen in the silcrete found at other archaeological deposits in the region. Given the association of the stone with the ash, we asked ourselves whether the ancient toolmakers might have exposed the silcrete to fire to make it easier to work with—a strategy that has been documented in ethnographic accounts of native North Americans and Australians. To find out, Brown carefully "cooked" some raw silcrete and then attempted to knap it. It flaked wonderfully, and the flaked surfaces shone with the same luster seen in the artifacts from our sites. We thus concluded that the Stone Age silcrete was also heat-treated.

We faced an uphill battle to convince our colleagues of this remarkable claim, however. It was archaeology gospel that the Solutrean people in France invented heat treatment about 20,000 years ago, using it to make their beautiful tools. To bolster our case, we used three independent techniques. Chantal Tribolo of the University of Bordeaux performed what is called thermoluminescence analysis to determine whether the silcrete tools from Pinnacle Point were intentionally heated. Then Andy Herries of the University of New South Wales in Australia employed magnetic susceptibility, which looks for changes in the ability of rock to be magnetized—another indicator of heat exposure among iron-rich rocks. Finally, Brown used a gloss meter to measure the luster that develops after heating and flaking and compare it with the luster on the tools he made. Our results, detailed last year in the journal *Science,* showed that intentional heat treatment was a dominant technology at Pinnacle Point by 72,000 years ago and that people there employed it intermittently as far back as 164,000 years ago.

The process of treating by heat testifies to two uniquely modern human cognitive abilities. First, people recognized that they could substantially alter a raw material to make it useful—in this case, engineering the properties of stone by heating it, thereby turning a poor-quality rock into high-quality raw material. Second, they could invent and execute a long chain of processes. The making of silcrete blades requires a complex series of carefully designed steps: building a sand pit to insulate the silcrete, bringing the heat slowly up to 350 degrees Celsius, holding the temperature steady and then dropping it down slowly. Creating and carrying out the sequence and passing technologies down from generation to generation probably required language. Once established, these abilities no doubt helped our ancestors outcompete the archaic human species they encountered once they dispersed from Africa. In particular, the complex pyrotechnology detected at Pinnacle Point would have given early modern humans a distinct advantage as they en-

DIGGING FOR DINNER

Geophytes, the underground energy-storage organs of certain kinds of plants (*left*), swell with edible carbohydrates at certain times of the year. The distinctive vegetation that hugs the southern coast of Africa, particularly the fynbos plants (*above*), produces especially nutritious and easily digested geophytes, which presumably served as a staple for the early modern humans who lived in this region during glacial stage 6.

COURTESY OF J. C. DE VYNCK

CUTTING-EDGE TECHNOLOGY

Stone tools found in PP13B include sophisticated implements such as microblades (*bottom two rows*), which would have been attached to a wooden shaft to form projectile weapons. The toolmakers also appear to have heat-treated the stone to make it easier to shape—a technique that was believed to have originated much later and in France.

PER-ANDERS PETTERSON

tered the cold lands of the Neandertals, who seem to have lacked this technique.

SMART FROM THE START

IN ADDITION to being technologically savvy, the prehistoric denizens of Pinnacle Point had an artistic side. In the oldest layers of the PP13B sequence, my team has unearthed dozens of pieces of red ochre (iron oxide) that were variously carved and ground to create a fine powder that was probably mixed with a binder such as animal fat to make paint that could be applied to the body or other surfaces. Such decorations typically encode information about social identity or other important aspects of culture—that is, they are symbolic. Many of my colleagues and I think that this ochre constitutes the earliest unequivocal example of symbolic behavior on record and pushes the origin of such practices back by tens of thousands of years. Evidence of symbolic activities also appears later in the sequence. Deposits dating to around 110,00 years ago include both red ochre and seashells that were clearly collected for their aesthetic appeal, because by the time they washed ashore from their deepwater home, any flesh would have been long gone. I think these decorative seashells, along with the evidence for marine foraging, signal that people had, for the first time, begun to embed in their worldview and rituals a clear commitment to the sea.

The precocious expressions of both symbolism and sophisticated technology at Pinnacle Point have major implications for understanding the origin of our species. Fossils from Ethiopia show that anatomically modern humans had evolved by at least 195,000 years ago. The emergence of the modern mind, however, is more difficult to establish. Paleoanthropologists use various proxies in the archaeological record to try to identify the presence and scope of cognitive modernity. Artifacts made using technologies that require outside-the-box connections of seemingly unrelated phenomena and long chains of production—like heat treatment of rock for tool manufacture—are one proxy. Evidence of art or other symbolic activities is another, as is the tracking of time through proxies such as lunar phases. For years the earliest examples of these behaviors were all found in Europe and dated to after 40,000 years ago. Based on that record, researchers concluded that there was a long lag between the origin of our species and the emergence of our peerless creativity.

But over the past 10 years archaeologists working at a number of sites in South Africa have found examples of sophisticated behaviors that predate by a long shot their counterparts in Europe. For instance, archaeologist Ian Watts, who works in South Africa, has described hundreds to thousands of pieces of worked and unworked ochre at sites dating as far back as 120,000 years ago. Interestingly, this ochre, as well as the pieces at Pinnacle Point, tends to be red despite the fact that local sources of the mineral exhibit a range of hues, suggesting that humans were preferentially curating the red pieces—perhaps associating the color with menstruation and fertility. Jocelyn A. Bernatchez, a Ph.D. student at Arizona State, thinks that many of these ochre pieces may have been yellow originally and then heat-treated to turn them red. And at Blombos Cave, located about 100 kilometers west of Pinnacle Point, Christopher S. Henshilwood of the University of Bergen in Norway has discovered pieces of ochre with systematic engravings, beads made of snail shells and refined bone tools, all of which date to around 71,000 years ago [see "The Morning of the Modern Mind," by Kate Wong; Scientific American, June 2005]. These sites, along with those at Pinnacle Point, belie the claim that modern cognition evolved late in our lineage and suggest instead that our species had this faculty at its inception.

I suspect that a driving force in the evolution of this complex cognition was strong long-term selection acting to enhance our ancestors' ability to mentally map the location and seasonal variation of many species of plants in arid environments and to convey this accumulated knowledge to offspring and other group members. This capacity laid the foundation for many other advances, such as the ability to grasp the link between the phases of the moon and the tides and to learn to schedule their shellfish-hunting trips to the shore accordingly. Together the readily available shellfish and geophytes provided a high-quality diet that allowed people to become less nomadic, increased their birth rates and reduced their child mortality. The larger group sizes that resulted from these changes would have promoted symbolic behavior and technological complexity as people endeavored to express their social identity and build on one another's technologies, explaining why we see such sophisticated practices at PP13B.

FOLLOW THE SEA

PP13B PRESERVES a long record of changing occupations that, in combination with the detailed records of local climate and environmental change my team has obtained, is revealing how our ancestors used the cave and the coast over millennia. Modeling the paleocoastline over time, Erich C. Fisher of the University of Florida has shown that the conditions changed quickly and dramatically, thanks to a long, wide, gently sloping continental shelf off the coast of South Africa called the Agulhas bank. During glacial periods, when sea levels fell, significant amounts of this shelf would have been exposed, putting considerable distance—up to 95 kilometers—between Pinnacle Point and the ocean. When the climate warmed and sea levels rose, the water advanced over the Agulhas bank again, and the caves were seaside once more.

Judging from rainfall and vegetation patterns evident in records from stalagmites spanning the time between 350,000 and 50,000 years ago, we see that the fynbos probably followed the retreating coast out onto the now submerged continental shelf and back again, keeping the geophytes and shellfish in close proximity. As for the people, during these periods of low population density they were free to target the best part of the landscape, and that was the intersection of the geophytes and shellfish—so I suspect they followed the sea. The tracking of resources would explain why PP13B appears to have been occupied intermittently.

Our excavations at PP13B have intercepted the people who may very well be the ancestors of everyone on the planet as they shadowed the shifting shoreline. Yet if I am correct about these people and their connection to the coast, the richest record of the progenitor population lies underwater on the Agulhas bank. There it will remain for the near future, guarded by great white sharks and dangerous currents. We can still test the hypothesis that humans followed the sea by examining sites on the current coast such as PP13B and another site we are excavating called PP5-6. But we can also study locations where the continental shelf drops steeply and the coast was always near—investigations that my colleagues and I are currently initiating.

The genetic, fossil and archaeological records are reasonably concordant in suggesting that the first substantial and prolonged wave of modern human migration out of Africa occurred around 50,000 years ago. But questions about the events leading up to that exodus remain. We still do not know, for example, whether at the end of glacial stage 6 there was just one population of *H. sapiens* left in Africa or whether there were several, with just one ultimately giving rise to everyone alive today. Such unknowns are providing my team and others with a very clear and exciting research direction for the foreseeable future: our fieldwork needs to target the other potential progenitor zones in Africa during that glacial period and expand our knowledge of the climate conditions just before that stage. We need to flesh out the story of these people who eventually pushed out of their refuge, filled up the African continent and went on to conquer the world. ■

PER-ANDERS PETTERSON

PROBING THE PAST

Continued excavation of PP13B (*above*) and other caves along the southern coast of Africa should reveal more about the progenitor population of humans who survived the bottleneck and colonized the globe.

MORE TO EXPLORE

The Origin of Modern Human Behavior: Critique of the Models and Their Test Implications. Christopher S. Henshilwood and Curtis W. Marean in *Current Anthropology,* Vol. 44, No. 5, pages 627–651; December 2003.

Early Human Use of Marine Resources and Pigment in South Africa during the Middle Pleistocene. Curtis W. Marean et al. in *Nature,* Vol. 449, pages 905–908; October 18, 2007.

Fire as an Engineering Tool of Early Modern Humans. Kyle S. Brown et al. in *Science,* Vol. 325, pages 859–862; August 14, 2009.

Coastal South Africa and the Coevolution of the Modern Human Lineage and the Coastal Adaptation. Curtis W. Marean in *Trekking the Shore: Changing Coastlines and the Antiquity of Coastal Settlement.* Edited by Nuno Bicho, Jonathan A. Haws and Loren G. Davis. Springer (in press).

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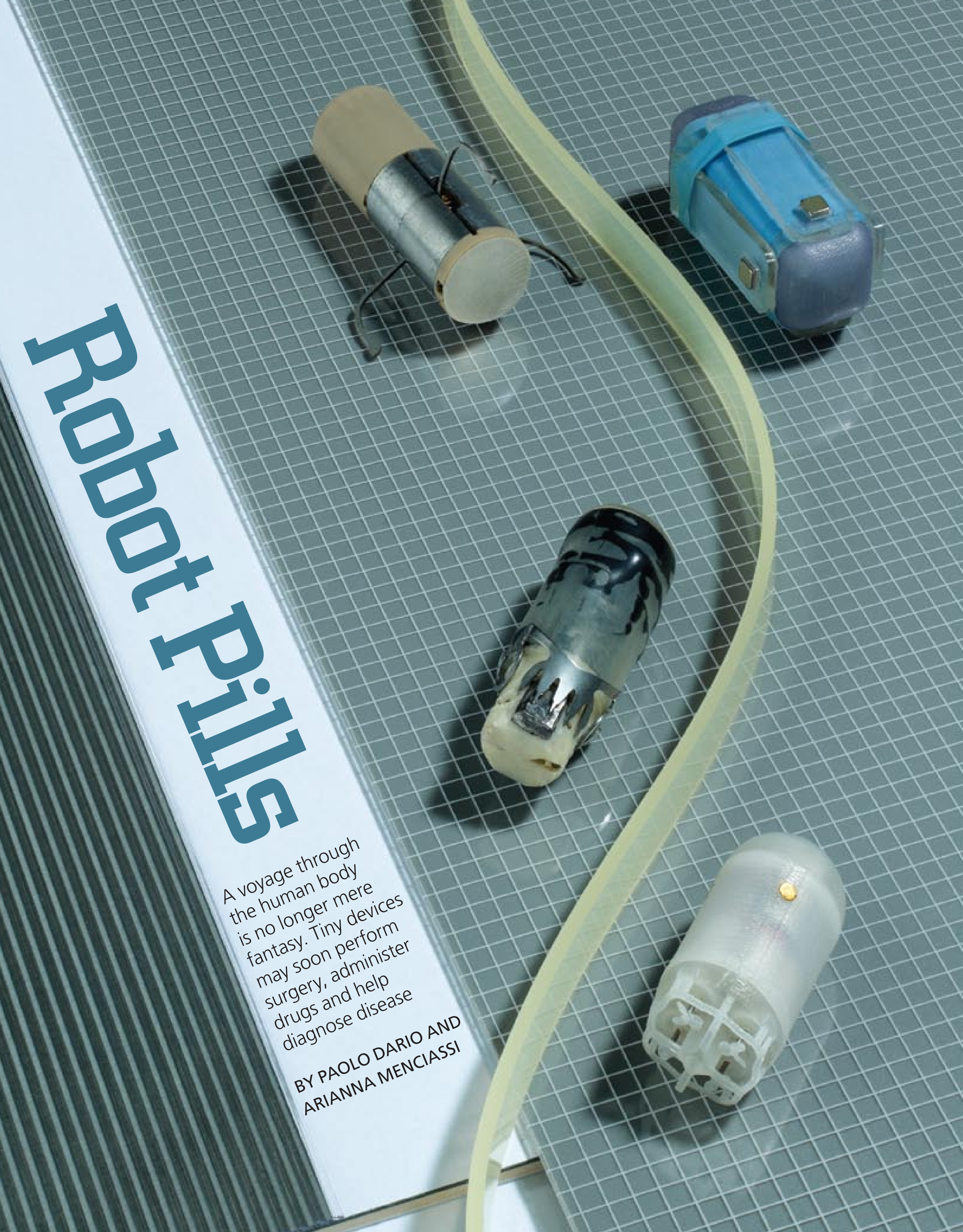
Robot Pills

A voyage through the human body is no longer mere fantasy. Tiny devices may soon perform surgery, administer drugs and help diagnose disease

BY PAOLO DARIO AND ARIANNA MENCIASSI



THE MOVIE *FANTASTIC VOYAGE,* the story of a miniaturized team of doctors traveling through blood vessels to make lifesaving repairs in a patient's brain, was pure science fiction when it came out in 1966. By the time Hollywood remade the film in 1987 as *Innerspace,* a comedy, real-world engineers had already begun building prototypes of pill-size robots that could voyage through a patient's gastrointestinal tract on a doctor's behalf. Patients began swallowing the first commercially built pill cameras in 2000, and since then doctors have used the capsules to get unprecedented views of places, such as the inner folds of the small intestine, that are otherwise difficult to reach without surgery.

One important aspect of *Fantastic Voyage* that has remained fantasy is the notion that such tiny pill cameras could maneuver under their own power, swimming toward a tumor to get a biopsy, checking out inflammation in the small intestine, or even administering drug treatments to an ulcer. In recent years, however, researchers have made great strides in converting the basic elements of a passive camera pill into an active miniature robot. Advanced prototypes, now being tested in animals, have legs, propellers, sophisticated imaging lenses and wireless guidance systems. Soon these tiny robots may be ready for clinical trials. Right now they are testing the limits of miniaturized robotics.

TRANSFORMING PASSIVE PILLS

THE DIGESTIVE TRACT is the first frontier. The first wireless camera pill, M2A, introduced in 1999 by the Israeli company Given Imaging, and subsequent models established the usefulness of examining the gastrointestinal tract with a wireless device. The practice, known as capsule endoscopy, is now routinely used in medicine. Unfortunately, the lack of human control in a passive camera pill leads to a high rate of false negative results—the cameras miss problem areas, which is unacceptable for a diagnostic tool. If the purpose of peering inside the body is to screen for disease or to get a closer look at a suspected problem, a doctor wants most of all to be able to stop the camera and maneuver it to inspect a region of interest.

Transforming a passive capsule into a more reliable device for gastrointestinal screening requires adding moving appendages, or actuators, to propel the pill through the body or act as tools for manipulating tissues. Operating those moving parts demands two-way high-speed wireless data transmission of images and instructions. The pills must, in effect, become tiny robots able to respond quickly to a technician's orders. All these components need sufficient power to complete their tasks during a journey that could last up to 12 hours. And all this must fit into a two-cubic-centimeter container—about the size of a Gummi Bear—that a patient can comfortably swallow.

The same year M2A debuted, the Intelligent Microsystem Center (IMC) in Seoul, Korea, initiated a 10-year project to develop a new generation of capsular endoscopes with advanced features. Such a robotic pill would have onboard sensors and a light source for imaging. It would have mechanisms for delivering drug therapies and taking biopsies. And it would have the ability to locomote, under an endoscopist's wireless remote control. Since 2000, additional companies and research groups have entered the field. For instance, 18 European teams formed a consortium with the IMC to develop capsular robots for cancer detection and treatment. Our group at the Scuola Superiore Sant'Anna in Pisa, Italy, with the medical supervision and guidance of Marc O. Schurr of novineon in Tubingen, Germany, handles the scientific and technical coordination of that project, called VECTOR, for *v*ersatile *e*ndoscopic *c*apsule for gastrointestinal *t*umor *r*ecognition and therapy.

These academic and industry groups have come up with many innovative ideas. In particular, they have posed a variety of solutions to the central challenge: how to control the movement of capsular devices inside the body. Most of them take one of two fundamental approaches.

The first entails directing the movement of the capsule with onboard actuators—moving parts such as paddles, legs, propellers or similar appendages integrated into the shell of the device and capable of deploying once the pill is inside the digestive tract. The actuators, powered by miniature motors, are most often used to direct the capsule's movements, but in some designs legs can also push aside tissue around the capsule, to get a better look at something or to help the capsule pass through a collapsed section of intestine. Motors and actuator mechanisms such as gears are pretty large compared with the total volume of a swallowable capsule, which makes the integration of other essential parts—the imaging sensor or a therapeutic module such as a biopsy tool—challenging. In addition, to distend tissue, a capsule must exert a significant force—equivalent to 10 or 20 times its weight. The ef-

KEY CONCEPTS

- Pill cameras made possible unprecedented internal views of the entire digestive tract, but the uses and accuracy of those passive capsules are limited.
- Active pill-size robotic capsules are being developed for use in screening, diagnosis and therapeutic procedures.
- Miniaturizing robotic components to perform tasks inside the body poses novel engineering challenges. Those challenges are giving rise to creative solutions that will influence robotics and other medical technologies in general.

—The Editors

FRANK HÜLSBÖMER

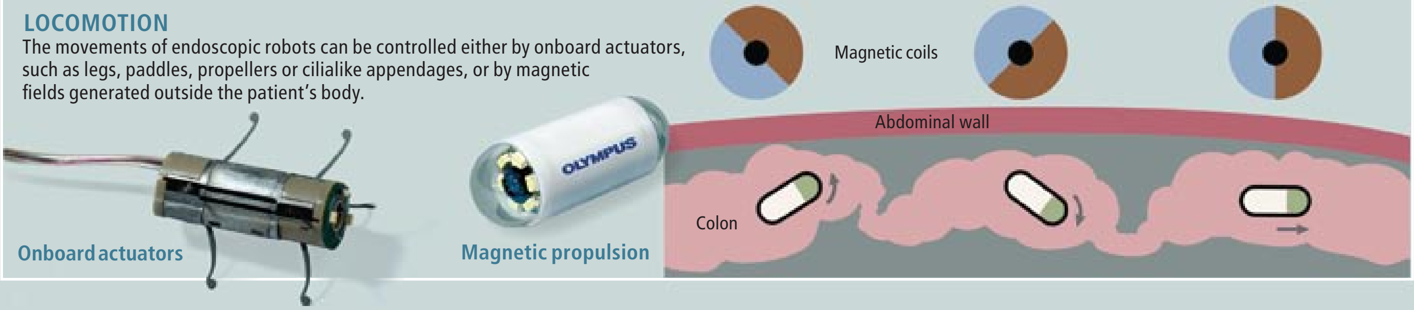
[IN THE WORKS]

MINI BOTS FOR A WIDE RANGE OF JOBS

To make miniature robots that can operate in the digestive tract, engineers must find ways of wirelessly controlling their locomotion and fine movements. And they must fit the required tools, imaging sensors and power supply into a capsule small enough for a patient to swallow. Here are some examples of the diverse tasks engineers want tiny robots to do and the ways they are trying to overcome the technical challenges.

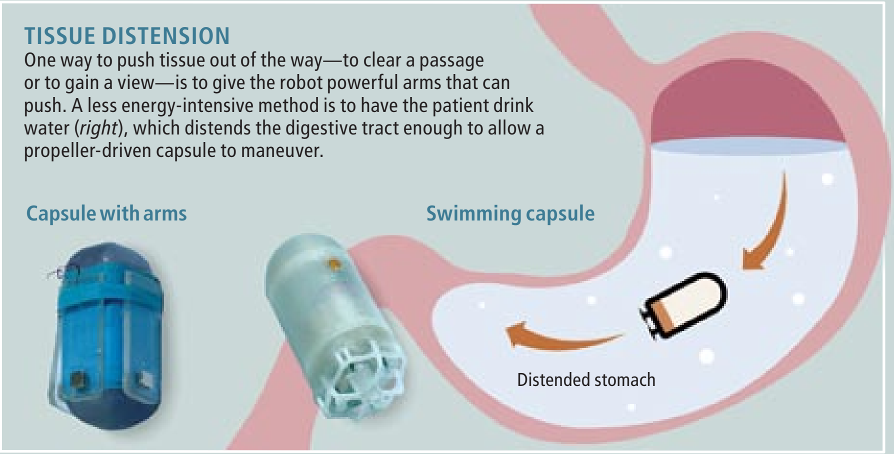
LOCOMOTION

The movements of endoscopic robots can be controlled either by onboard actuators, such as legs, paddles, propellers or cilialike appendages, or by magnetic fields generated outside the patient's body.



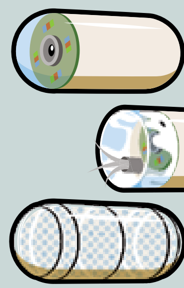
TISSUE DISTENSION

One way to push tissue out of the way—to clear a passage or to gain a view—is to give the robot powerful arms that can push. A less energy-intensive method is to have the patient drink water (*right*), which distends the digestive tract enough to allow a propeller-driven capsule to maneuver.



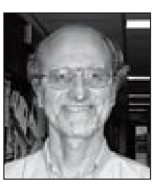
DIAGNOSIS/TREATMENT

A capsule can carry a wide range of tools: a spectroscopic camera that sees cells underneath the surface layer of tissue; a clip for taking a tissue biopsy; or a well that holds a dose of medication.



[THE AUTHORS]

PAOLO DARIO and **ARIANNA MENCIASSI** are professors of biomedical robotics at the Scuola Superiore Sant'Anna in Pisa, Italy. Dario, inventor of the first self-propelled colonoscopic robot in the 1990s, has also pioneered wireless robotic capsular endoscopes through work with South Korea's Intelligent Microsystems Center and partnerships with European robotics investigators. Menciassi, who has collaborated with Dario for 10 years, specializes in microengineering for minimally invasive therapies and medical nanotechnology.




fort requires high torques from the motors, which consumes considerable power (approximately half a watt). This power drain puts a strain on battery technology, which limits how long these devices can operate.

To conserve battery power, the best trade-off might be to use actuators only for propulsion and find other ways to distend tissue. Having a patient drink half a liter of clear liquid just before swallowing a propeller-driven capsule, for instance, would distend the stomach for up to 20 minutes before the fluid drains away into the small intestine. In that time, the pill could swim around under wireless control and examine the stomach lining.

The bulk and power requirements of onboard actuators have led some researchers to focus on another approach: applying magnetic fields generated outside the body to remotely control the movement of the capsules. In 2005 Olympus and Siemens introduced a magnetic guidance system for its passive camera pill that causes the pill to rotate. The corkscrew motion generates a light friction that helps the capsule burrow through narrow stretches of the digestive tract, such as the small intestine, according to literature from Siemens.

Although using magnets to guide an endoscopic capsule through the intestines is straightforward, achieving reliable control with magnets alone is extremely difficult. Magnetic fields lose power with distance, and with the irregular geometry of the intestine, sudden changes in field strength can cause the capsule to jump or can entirely sever magnetic control over the pill. In practice, this instability may cause an operator to lose contact with the pill and to be unable to find it again. It is possible to compensate by adding more magnets, which would give greater control and stability, but that might require cumbersome configurations of the electromagnetic coils.

TAILORED HYBRIDS

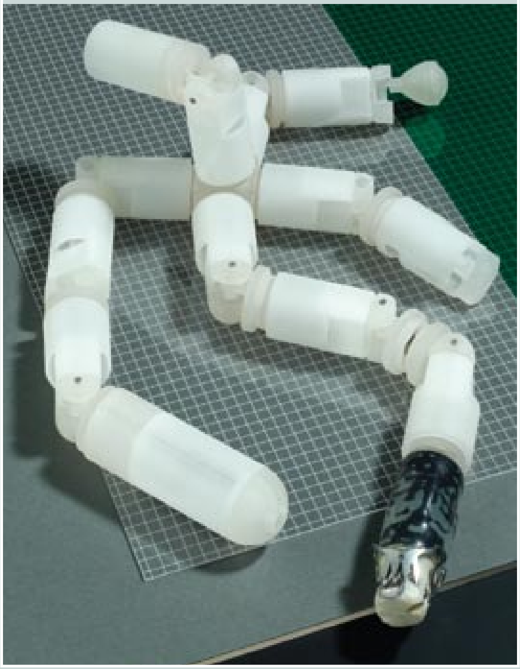
IN LIGHT OF the limitations of both internal and external approaches to controlling capsule movements, we believe that we need to combine these

FRANK HÜLSBÖMER (*three capsules*); COURTESY OF SIEMENS (*magnetic propulsion capsule*); JOSH MCKIBLE (*illustrations*); COURTESY OF FEDERICA RADICI (*Dario*); COURTESY OF ARIANNA MENCIASSI (*Menciassi*)

REMOTE SURGERY

One way to expand the range of tasks that robot pills can perform is to design them for self-assembly. The patient would swallow a dozen or more pills; once inside the stomach, the pills would combine with one another to form one big, powerful robot. Surgeons would operate the device wirelessly. When the surgery was completed, the robot would break apart into capsules, which would pass harmlessly through the digestive tract.

Possible surgical configuration



two methods to find a solution that will be comfortable for the patient and offer reliable diagnostics. External magnetic locomotion is adequate for a rough positioning of a capsule inside the intestine; leglike actuators are useful to shift position or maneuver for a better view.

Our research group has designed such a hybrid capsule with four motor-driven legs and tested it in a pig, whose intestines are the same dimensions as those of humans. The capsule's legs remain closed while the device is being swallowed and during most of its trip through the digestive tract. An external magnetic field generator held close to the abdomen guides the capsule forward. When the capsule reaches a segment of intestine whose walls have collapsed, it lifts the surrounding tissue by extending its legs, which move the capsule slightly forward through the opening.

In most areas of the small and large intestines, a hybrid locomotion system would provide the control doctors need for thorough visual inspection. Different situations will call for different solutions. The VECTOR project, for instance, has developed three capsule concepts for the small intestine alone: one is a passive camera pill for normal screening; a second is a diagnostic capsule with active locomotion and spectroscopic imaging that can detect abnormalities underneath the tissue surface. The same spectroscopic sensor is incorporated in the third planned VECTOR capsule, which would also carry a biopsy tool that could take a tissue sample and store it inside the capsule, to be retrieved when the capsule exits the patient.

The ability to perform biopsies and other more complex therapeutic actions, such as surgical procedures, would make capsular endoscopic robots an even more powerful medical tool. But critical problems such as power supply, space constraints and limited torque make many more ambitious therapeutic tasks requiring complicated motions and multiple actuators impossible to achieve with a single two-cubic-centimeter pill.

For these reasons, we are now working on an advanced concept: surgical robots that configure themselves inside the body. Here is how it might work. The patient would drink a stomach-distending fluid, then swallow as many as 10 to 15 capsules. Each capsule would be a miniaturized component with magnets at either end. Once inside the stomach, the capsules, under remote guidance, would quickly assemble themselves into the desired configuration. A surgeon would then use the assembled robot as a wireless tool that can operate without the need to make a single incision from outside the body. When the surgery is done, the magnetic bonds between the capsules could be reconfigured or broken, allowing the parts to make their exit harmlessly through the digestive tract.

We have an early prototype based on two-centimeter capsules with customizable internal parts and actuators. One or more capsules could have a camera, others could have onboard tools, and all would be controlled wirelessly.

Miniaturized robotic components may eventually find wider use throughout the body for a variety of purposes. Guidance systems and camera sensors developed for capsule endoscopy are already influencing related biomedical technologies, such as the newest versions of traditional endoscopes and laparoscopic surgery tools. Beyond health care, these technologies are part of a broad trend toward miniaturization and wirelessly controlled multifunctional robotics. Capsule robots will undoubtedly have an influence on robotic machines in the larger world. ■

HYBRID CAPSULE guided by external magnets navigates the colon of a pig, using extendable legs to adjust its position and push aside tissue.

FRANK HÜLSBÖMER (*left*); COURTESY OF ARIANNA MENCIASSI (*right*)

MORE TO EXPLORE

Wireless Capsule Endoscopy: From Diagnostic Devices to Multipurpose Robotic Systems. Andrea Moglia, Arianna Menciassi, Marc Oliver Schurr and Paolo Dario in *Biomedical Microdevices,* Vol. 9, No. 2, pages 235–243; December 12, 2006.

Wireless Therapeutic Endoscopic Capsule: In Vivo Experiment. P. Valdastri et al. in *Endoscopy 2008,* Vol. 40, No. 12, pages 979–982; December 2008.

Wireless Reconfigurable Modules for Robotic Endoluminal Surgery. Kanako Harada, Ekawahyu Susilo, Arianna Menciassi and Paolo Dario in *Proceedings of the 2009 IEEE International Conference on Robotics and Automation.* Kobe, Japan, May 2009.

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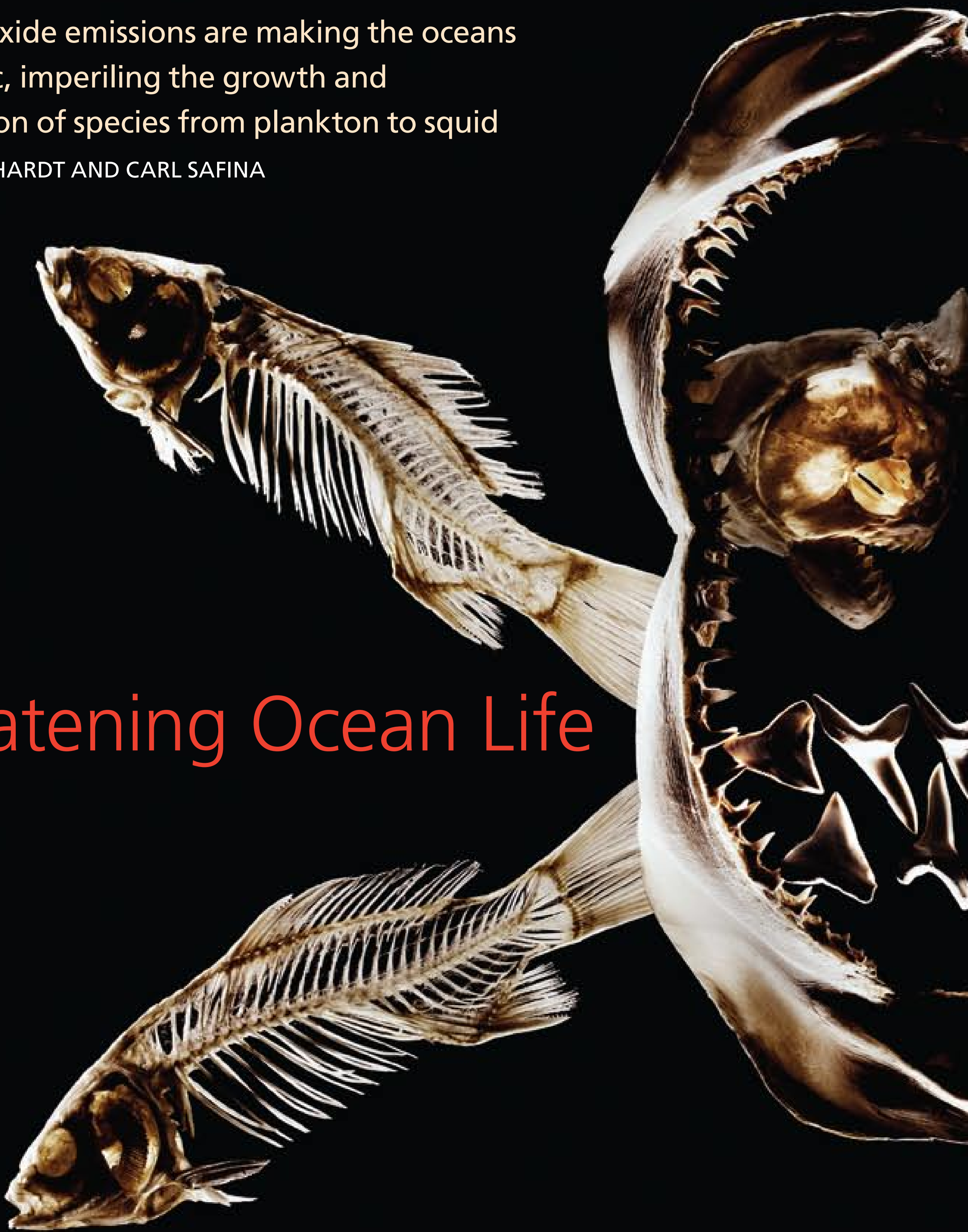
Carbon dioxide emissions are making the oceans more acidic, imperiling the growth and reproduction of species from plankton to squid

BY MARAH J. HARDT AND CARL SAFINA

Threatening Ocean Life



PHOTOGRAPH BY JAMIE CHUNG

from the Inside Out

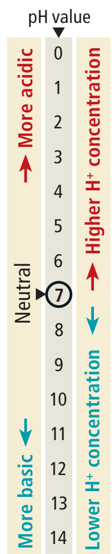
KEY CONCEPTS

- The pH of seawater worldwide is dropping (acidifying) as oceans absorb ever more carbon dioxide from the atmosphere.
- Experiments show that the struggle by copepods, snails, sea urchins and brittlestars to balance the changing pH inside their bodies impairs their ability to reproduce and grow. Many species are unlikely to genetically adapt to ocean acidification, because the change is occurring too quickly.
- As species wither, the marine food chain could be disrupted; human action is needed to curtail further acidification.

—The Editors

pH PRIMER

The pH of a solution is determined by the concentration of hydrogen ions (H^+) in it. A value of 7.0 is neutral; lower is acidic; higher is basic. "Acidification" means a drop in value, anywhere along the scale.



SLOW SPERM ... now that's a problem," said Jonathan Havenhand, his British accent compounding the gravity of the message. "That means fewer fertilized eggs, fewer babies and smaller populations." We were sharing a hilly cab ride along the glistening northern coast of Spain to attend an international symposium about the effects of climate change and excess atmospheric carbon dioxide on the world's oceans. As researchers, we were concerned about the underappreciated effects of changing ocean chemistry on the cells, tissues and organs of marine species. In laboratory experiments at the University of Gothenburg in Sweden, Havenhand had demonstrated that such changes could seriously impede the most fundamental strategy of survival: sex.

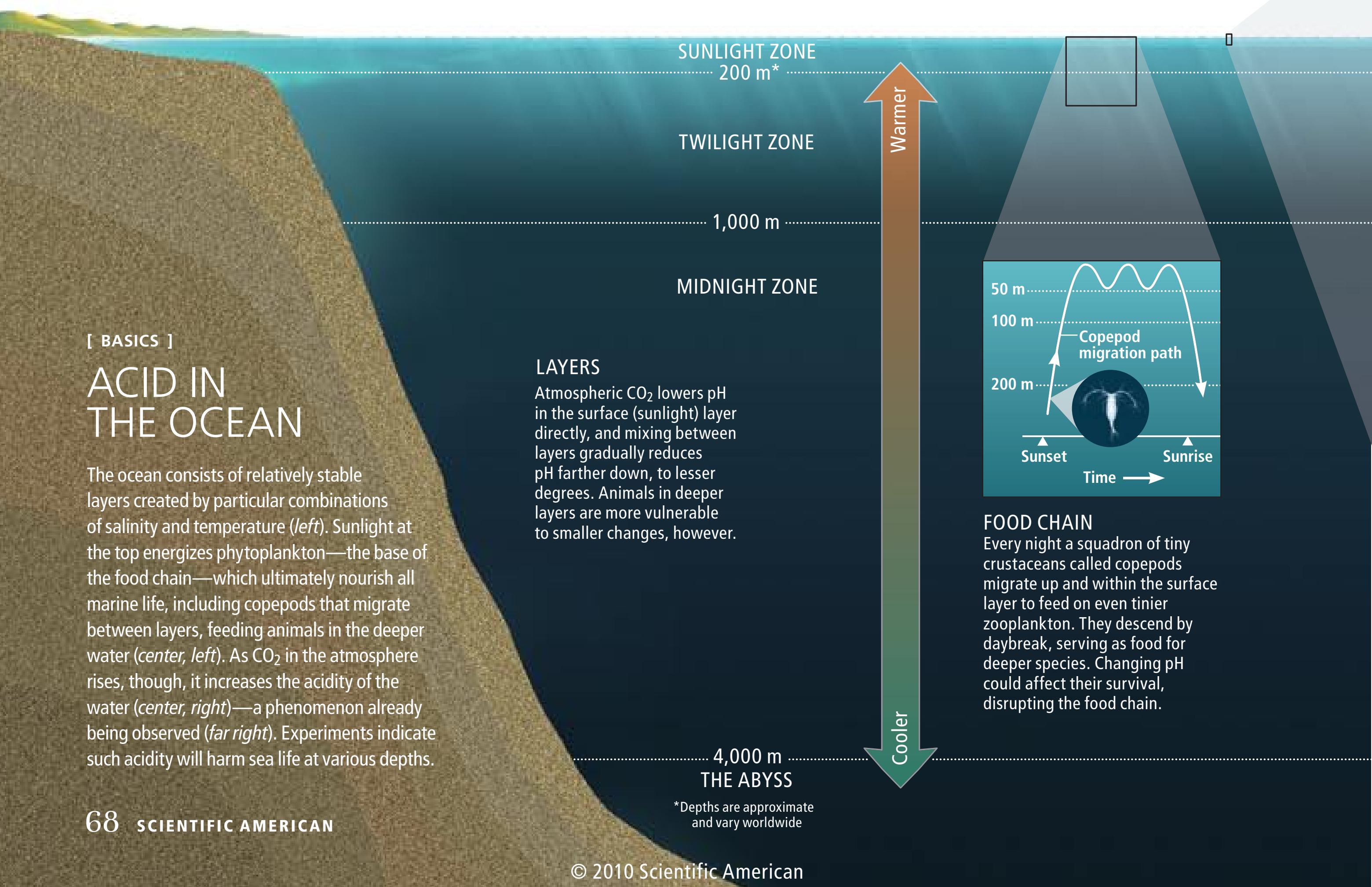
Ocean acidification—a result of too much carbon dioxide reacting with seawater to form carbonic acid—has been dubbed "the other CO_2 problem." As the water becomes more acidic, corals and animals such as clams and mussels have trouble building their skeletons and shells. But even more sinister, the acidity can interfere with basic bodily functions for all marine animals, shelled or not. By disrupting processes as fundamental as growth and reproduction, ocean acidification threatens the animals' health and even the survival of species. Time is running out to limit acidification before it irreparably harms the food chain on which the world's oceans—and people—depend.

RAPID SEA CHANGE

THE OCEAN'S INTERACTION with CO_2 mitigates some climate effects of the gas. The atmospheric CO_2 concentration is almost 390 parts per million (ppm), but it would be even higher if the oceans didn't soak up 30 million tons of the gas every day. The world's seas have absorbed roughly one third of all CO_2 released by human activities. This "sink" reduces global warming—but at the expense of acidifying the sea. Robert H. Byrne of the University of South Florida has shown that in just the past 15 years, acidity has increased 6 percent in the upper 100 meters of the Pacific Ocean from Hawaii to Alaska. Across the planet, the average pH of the ocean's surface layer has declined 0.12 unit, to approximately 8.1, since the beginning of the industrial revolution.

That change may not sound like much, but because the pH scale is logarithmic, it equates to a 30 percent increase in acidity. Values of pH

GEORGE RETSECK (*main illustration*)



[BASICS]

ACID IN THE OCEAN

The ocean consists of relatively stable layers created by particular combinations of salinity and temperature (*left*). Sunlight at the top energizes phytoplankton—the base of the food chain—which ultimately nourish all marine life, including copepods that migrate between layers, feeding animals in the deeper water (*center, left*). As CO_2 in the atmosphere rises, though, it increases the acidity of the water (*center, right*)—a phenomenon already being observed (*far right*). Experiments indicate such acidity will harm sea life at various depths.

LAYERS
Atmospheric CO_2 lowers pH in the surface (sunlight) layer directly, and mixing between layers gradually reduces pH farther down, to lesser degrees. Animals in deeper layers are more vulnerable to smaller changes, however.

FOOD CHAIN
Every night a squadron of tiny crustaceans called copepods migrate up and within the surface layer to feed on even tinier zooplankton. They descend by daybreak, serving as food for deeper species. Changing pH could affect their survival, disrupting the food chain.

measure hydrogen ions (H^+) in solution. A value of 7.0 is neutral; lower values are increasingly acidic, and higher values are basic. Although 8.1 is mildly basic, the declining trend constitutes acidification. Marine life has not experienced such a rapid shift in millions of years. And paleontology studies show that comparable changes in the past were linked to widespread loss of sea life. It appears that massive volcanic eruptions and methane releases around 250 million years ago may have as much as doubled atmospheric CO_2, leading to the largest mass extinction ever. More than 90 percent of all marine species vanished. A completely different ocean persisted for four million to five million years, which contained relatively few species.

If we continue to emit greenhouse gases at current rates, scientists estimate that atmospheric CO_2 will reach 500 ppm by 2050 and 800 ppm by 2100. The pH of the upper ocean could drop to 7.8 or 7.7—as much as a 150 percent increase in acidity compared with preindustrial times.

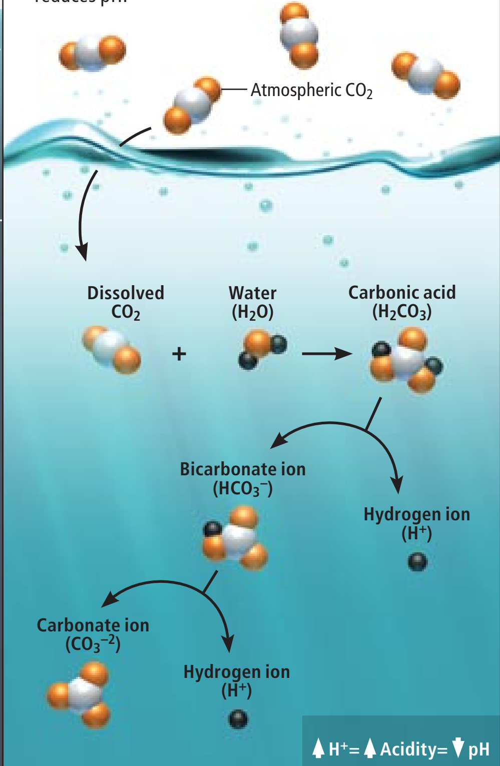
Most people envision the ocean as a giant pool of water. But the ocean is more like a layer cake, with each layer created by unique combinations of salinity and temperature. The warmest and freshest (least salty) floats from the surface down 50 to 200 meters, sometimes deeper. Plentiful oxygen and sunlight support the blooming base of the food chain: single-celled phytoplankton that, like plants, use sunlight to create sugar. The phytoplankton nourish zooplankton—small animals ranging from minuscule shrimplike crustaceans to the larvae of giant fish. Zooplankton are eaten by small fish, which feed bigger animals, and so on.

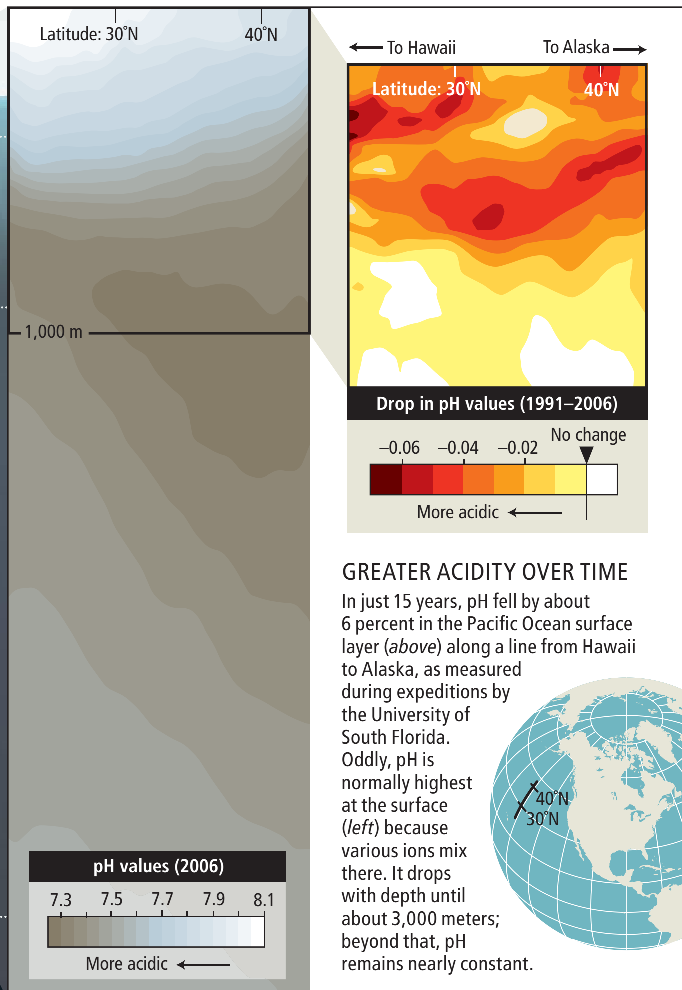
Winds help to mix the surface and deeper layers, sending oxygen down and bringing nutrients up. But the flux of nutrients between surface and seafloor also occurs through the movement of animals, alive and dead. An extensive class of tiny crustaceans called copepods migrate every night, under the cover of darkness, from middle

Geologic records show that comparable pH changes in the past wiped out almost all sea life.

ACID CREATION

Carbon dioxide molecules in the air are absorbed by seawater at the surface. The CO_2 then reacts with the water (H_2O) to form carbonic acid (H_2CO_3). Most of this weak acid dissociates into hydrogen ions (H^+) and bicarbonate ions (HCO_3^-). Some bicarbonate also dissociates, producing more H^+. The increase in H^+ ions reduces pH.





GREATER ACIDITY OVER TIME

In just 15 years, pH fell by about 6 percent in the Pacific Ocean surface layer (*above*) along a line from Hawaii to Alaska, as measured during expeditions by the University of South Florida. Oddly, pH is normally highest at the surface (*left*) because various ions mix there. It drops with depth until about 3,000 meters; beyond that, pH remains nearly constant.

JEN CHRISTIANSEN (*right panel*); SOURCE: "DIRECT OBSERVATIONS OF BASIN-WIDE ACIDIFICATION OF THE NORTH PACIFIC OCEAN," BY ROBERT H. BYRNE ET AL., IN *GEOPHYSICAL RESEARCH LETTERS*, VOL. 37, L02601; JANUARY 20, 2010

Emissions targets should limit pH declines to no more than 0.1 over the next century, given the consequences.

and even deep layers to the surface to dine on the banquet created by the day's rays. Many fish and squid follow their movements, while deep dwellers wait for that bountiful food to rain down, in the form of sinking remains. As organisms rise and fall, they pass through waters with different pH values. But as acidification changes this pH profile, it could harm the organisms.

THE INSIDE ANGLE

AT THE SCALE of individual marine animals, acidification can force creatures to spend more energy on restoring and maintaining their internal pH balance, diverting energy away from important processes such as growth and reproduction.

Even small increases in seawater CO_2 concentration can cause rapid diffusion into the bodies of water-breathing animals. Once inside, CO_2 reacts with internal fluids, creating hydrogen ions, making the bodily fluids or tissue more acidic. Species employ various mechanisms to balance their internal pH. These actions include producing negative ions such as bicarbonate that soak up, or buffer, the extra hydrogen ions; pumping ions in and out of cells and intercellular spaces; and reducing metabolism to absorb fewer ions and "wait out" the period of high H^+ concentration. But none of these mechanisms is meant to handle a sustained drop in pH. As an organism struggles to regain an acid-base balance, it sacrifices energy. Basic life functions such as synthesizing protein and maintaining a strong immune system can also become compromised.

Most species possess at least some buffer molecules. Fish and other active species stockpile them to reduce temporary pH declines that result from extended swimming bursts. Just like in a runner, muscles shift to anaerobic (nonoxygen based) metabolism during sprints, which uses up ATP (the main fuel molecule) more quickly, causing extra H^+ ions to accumulate. But few species can stockpile enough buffering to last across extended timescales. If small pH changes occurred gradually over tens of thousands of years, a species might evolve adaptations, for example, by retaining chance genetic mutations that result in greater production of buffer molecules. But species generally cannot adapt to changes occurring over mere hundreds of years or less. Similar changes produced in the lab over days to weeks are lethal.

In past eras when CO_2 concentrations rose, species with less well-buffered systems fared poorly. Declines in pH may especially harm deep-sea species, whose stable environment leaves them ill equipped to adapt to change. (For this reason, proposed strategies to combat climate change by pumping large quantities of CO_2 into the deep sea are worrisome; they could destabilize the habitats of a wide array of creatures.)

POOR GROWTH AND REPRODUCTION

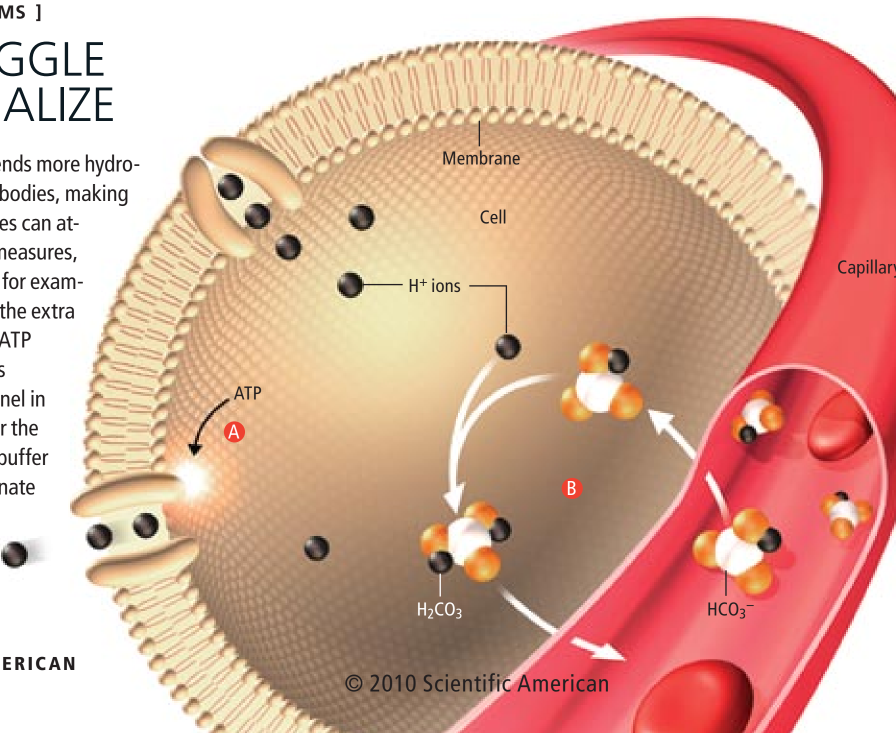
THE INTERNAL EFFECTS of ocean acidification vary across different developmental stages of life. A small but growing body of research points to a variety of potential trouble.

Indeed, the very first spark of life—fertilization—can be affected. In the lab, scientists sim-

[DEFENSE MECHANISMS]

THE STRUGGLE TO NEUTRALIZE

More CO_2 in seawater sends more hydrogen ions inside animals' bodies, making tissue more acidic. Species can attempt different countermeasures, but all sap energy. Cells, for example, can try to pump out the extra H^+ ions: energy from an ATP molecule pushes the ions through a one-way channel in the cell membrane (*a*). Or the body can produce more buffer molecules such as carbonate (HCO_3^-) that bind to the H^+ ions and carry them away (*b*).



▸ CRIPPLED CRITTERS

Laboratory experiments show that the development and fertility of ocean animals suffer in more acidic waters. After being raised for eight days in 8.1 pH water, typical of today's oceans, the larvae of brittlestars were mature and symmetric (*left, top*), but larvae raised at 7.7 pH were deformed (*left, bottom*), and none reached full development. Snail eggs fertilized and raised at 8.05 pH all had embryos, which had grown shells after 18 days (*right, top*), but in 7.6 pH water (*right, bottom*) some eggs were empty, and embryos had still not developed shells.

GEORGE RETSECK (*illustration*); "NEAR-FUTURE LEVEL OF CO_2-DRIVEN OCEAN ACIDIFICATION RADICALLY AFFECTS LARVAL SURVIVAL AND DEVELOPMENT IN THE BRITTLESTAR *OPHIOTHRIX FRAGILIS*," BY SAMUEL DUPONT ET AL., IN *MARINE ECOLOGY PROGRESS SERIES*, VOL. 373; 2008 (*brittlestar*); ROBERT SUTTON *University of Plymouth* (*eggs*) ulate acidification by pumping extra CO_2 bubbles through seawater tanks. As Havenhand had explained during our cab ride, sperm of the Australian sea urchin *Heliocidaris erythrogramma* moved 16 percent less and swam 12 percent slower when experimenters lowered seawater pH by 0.4 (within the range predicted by 2100). Fertilization success dropped by 25 percent. In the wild, a 25 percent reduction could lead to significantly diminished adult populations over time. Although individual sea urchins release millions of sperm and eggs, the sperm do not remain viable for very long; they have to find and fertilize an egg within a few minutes. In a big, turbulent ocean, sluggish sperm may never reach their destination at all.

Acidification also thwarts early larval stages of several species. Samuel Dupont, down the hall from Havenhand at Gothenburg, exposed larvae of a temperate brittlestar—a relative of the common sea star—to pH reduced by 0.2 to 0.4 unit. Many showed abnormal development, and fewer than 0.1 percent survived more than eight days. In another study, fewer embryos of the snail *Littorina obtusata* hatched when exposed to lower pH waters, and those that did hatch moved less frequently and more slowly than normal.

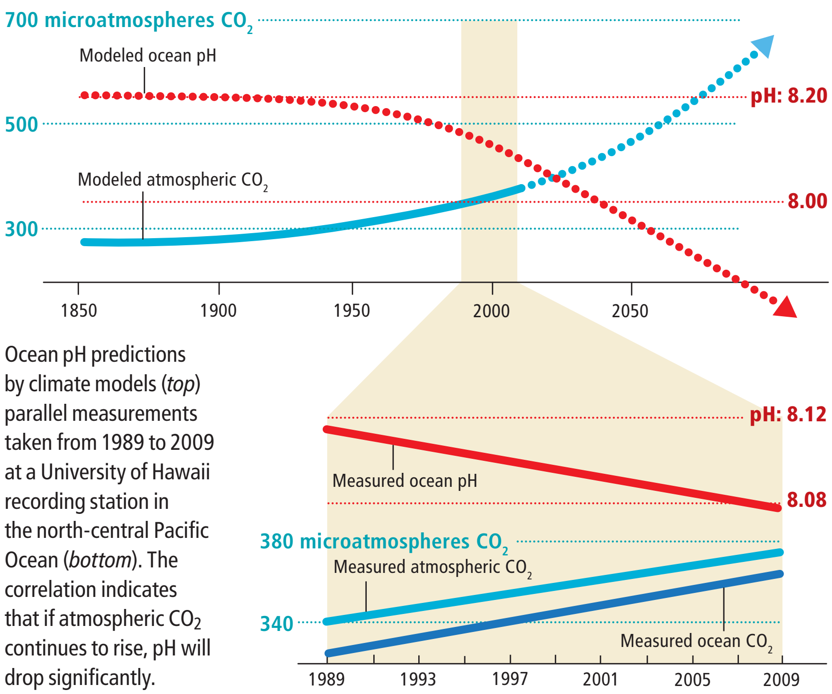
A change of 0.2 to 0.4 pH all at once is more dramatic than species in the wild are experiencing, and some species might be able to adapt to gradual change. But for others, the effects of even slight acidification come on strong and fast. Scientists suspect ocean acidification explains recent mortality in larval oysters along the coast of Oregon, for example, sending some oyster growers scrambling to find enough babies to stay in business.

Adult animals suffer as well, especially when it comes to growth. Sea urchins and snails move slowly, but *growing* slowly is problematic. In 2005 researchers at Kyoto University in Japan determined that a CO_2 concentration 200 ppm higher than today's value, pumped into seawater for six months, reduced growth rates for the sea urchin species *Hemicentrotus pulcherrimus* and *Echinometra mathaei* and for the strawberry conch *Strombus luhuanu*. The 200-ppm increase is equal to that predicted over the next four to five decades. Slowed growth leaves individuals smaller for longer, making them more susceptible to predators and potentially reducing their reproductive output.

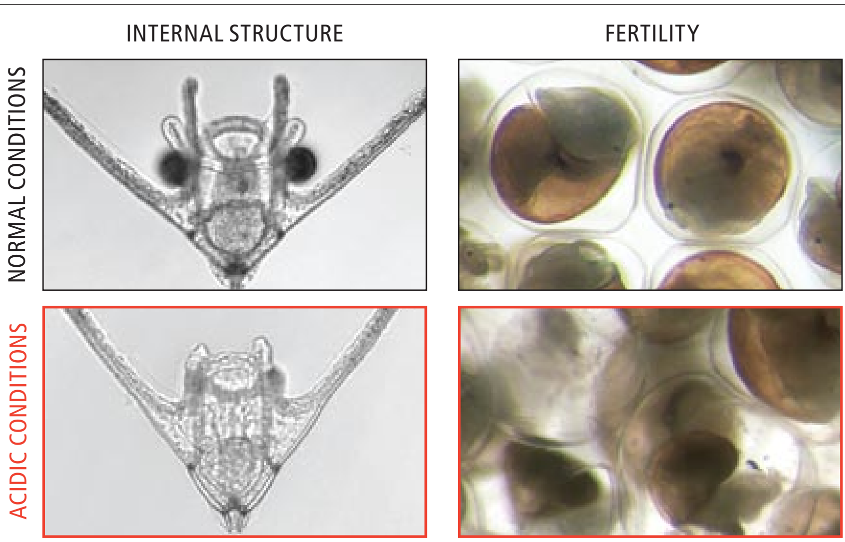
Acidification also makes it harder for some phytoplankton species to absorb iron, a micronutrient critical for growth. Researchers at Princeton University indicate that a 0.3 pH decline could reduce phytoplankton iron uptake by 10 to 20 percent. In addition to being an important link in the food chain, phytoplankton produce vast amounts of oxygen that we breathe.

In other experiments, the sediment-dwelling brittlestar *Amphiura filiformis* grew arms at greater rates under lower pH but lost significant muscle mass. Strong muscles are required for

MODELS VS. MEASUREMENTS IN THE PACIFIC



Ocean pH predictions by climate models (*top*) parallel measurements taken from 1989 to 2009 at a University of Hawaii recording station in the north-central Pacific Ocean (*bottom*). The correlation indicates that if atmospheric CO_2 continues to rise, pH will drop significantly.



JEN CHRISTIANSEN (*graphs*); SOURCES: "DIRECT EFFECTS OF CO_2 CONCENTRATION ON GROWTH AND ISOTOPIC COMPOSITION OF MARINE PLANKTON," BY DIETER A. WOLF-GLADROW ET AL., IN *TELLUS SERIES B-CHEMICAL AND PHYSICAL METEOROLOGY*, VOL. 51, NO. 2; 2002, AND "PHYSICAL AND BIOGEOCHEMICAL MODULATION OF OCEAN ACIDIFICATION IN THE CENTRAL NORTH PACIFIC," BY JOHN E. DORE ET AL., IN *PNAS*, VOL. 106, NO. 30; JULY 28, 2009 feeding, building burrows and escaping predators. A pH decline of 0.3 to 0.5 suppressed the immune system response of the common blue mussel within one month. Reduced strength, growth, immune function or reproduction can cause long-term population declines—bad news for the victims, as well as for the many other species (including humans) that rely on them for food and even habitat. Grazing by sea urchins, for example, helps to keep coral reefs and kelp forests healthy, and the mixing of sediments by the brittlestars' movements is critical to making the sediments livable for many other species.

For some creatures, ocean acidification can simply mean the end. When a sample of copepod species common off the California coast (*Paraeuchaeta elongata*) was exposed to water that was 0.2 pH below normal, half of the organisms died within a week. The fish we prefer to eat, from tuna to salmon or striped bass, depend on an abundance of specific copepods to support the prey that supports them.

Several species of fish, such as the spotted wolffish (*Anarhichas minor*), have shown remarkable tolerance in the lab, because they maintain a relatively large stockpile of buffers and store extra oxygen in their tissue, which is handy because H^+ ions interfere with the blood's ability to absorb oxygen from the water. Even very adaptable fish, however, may struggle if their food supply dwindles. Other species are not so well prepared. Highly active squid, for example, have no oxygen stores—they use all they have all the time. Less oxygen in their blood would limit their ability to hunt, avoid predators and find mates. For the commercially important squid *Illex illecebrosus*, a pH drop of just 0.15 could cause significant harm.

The message of lab studies as well as the geologic record is that ocean acidification forces animals to struggle harder, which today they are already doing because of other human-induced stressors such as warming waters, pollution and overfishing.

ACID ADAPTATION?

LAB EXPERIMENTS PERSIST for weeks to months. Climate change occurs over decades and centuries. Some species could adapt, especially if they have a short reproductive cycle. Each time an animal reproduces, genetic mutations can arise in the offspring that might help the next generation adjust to new circumstances. Ninety years—the predicted time frame for pH to decline by 0.3 to 0.5 unit—is extremely short, however, for genetic adaptation by species that reproduce at relatively slow rates and that may already be stressed by the 30 percent pH decrease. Species extinctions often result from slow declines over centuries or more; a decline of just 1 percent of individuals per generation could cause extinction in less than a century.

Alarmingly, the pH drop observed so far and the predicted trajectory under current emissions trends are 100 times faster than any changes in prior millennia. Left unchecked, CO_2 levels will create a very different ocean, one never experienced by modern species.

Adaptation is even more unlikely because the effects of acidification, and the other struggles creatures face, interact. For example, increased CO_2 levels can narrow the temperature range in which an individual can survive. We already see such constraints on corals and some algae, which become heat-stressed at lower temperatures than normal if exposed to higher CO_2.

OPTIONS FOR THE FUTURE

SCIENTISTS HAVE CONSISTENTLY underestimated rates of climate change, from Arctic ice melt to sea-level rise. Increasingly, experts recommend limiting atmospheric CO_2 to prevent dangerous levels of global warming. But the targets should be set with ocean acidification in mind as well. Unabated acidification could completely restructure marine ecosystems, with cascading effects across the food chain. Some species might thrive on a new combination of plankton while others suffer, but there is no telling if the species that we depend on most (or like the best) will be the winners. The changes could also hurt tourism and erase potential pharmaceutical and biomedical resources.

Ocean acidification also changes the rules for the planet's entire carbon cycle. Although the oceans now absorb a vast quantity of human emissions, the absorption rate slows as the seawater CO_2 concentration increases, and CO_2 "backs up" at the sea surface. As a result, atmospheric CO_2 concentration will rise even faster, accelerating global weather changes.

Such consequences warrant emissions targets that limit pH declines to no more than 0.1 over the next century. More and more, reducing the atmospheric CO_2 level to 350 ppm seems like the rational target. Stabilizing at 450 ppm by 2100, as some have suggested, could perhaps keep an additional pH decline to 0.1. But even that number could doom coral reefs and make it impossible for some animals to build shells, especially

[THE AUTHORS]

MARAH J. HARDT, founder of OceanInk, is a research scientist, writer and consultant on the Big Island of Hawaii. A coral reef ecologist by training and a former fellow at the Blue Ocean Institute in Cold Spring Harbor, N.Y., she works to solve diverse issues ranging from global overfishing to freshwater conservation. CARL SAFINA is founding president of the Blue Ocean Institute and an adjunct professor at Stony Brook University. A MacArthur Fellow, he is author of *Song for the Blue Ocean: Encounters along the World's Coasts and beneath the Seas* and *Eye of the Albatross: Visions of Hope and Survival*. Safina's upcoming book *The View from Lazy Point: A Natural Year in an Unnatural World* will appear this year.

FUTURE DATA

Carbon dioxide and pH sensors were deployed on buoys in the Pacific Ocean in December 2009 by the Scripps Institution of Oceanography, which provides data to California Current Ecosystem research projects. Such information will improve forecasts of ocean acidification trends.

COURTESY OF MARCY HARDT (*Hardt*); COURTESY OF PATRICIA PALADINES (*Safina*); COURTESY OF UWE SEND'S LAB, HTTP://MOORING.UCSD.EDU (*buoy*)

[SENSORY CONFUSION]

THE NEW LSD

Increasingly acidic ocean water interferes with the internal body chemistry of many species. Researchers are also finding that acidification may be altering survival in other unusual ways.

For example, many marine species use subtle olfactory cues to seek prey, mates or suitable habitat. Certain clownfish differentiate between attractive and repulsive smells to decide which reef and anemone to settle on for the rest of their days. In laboratory studies, clownfish larvae raised in seawater with a pH 0.2 to 0.4 lower than today's ocean average swim toward negative cues and do not respond to positive ones. Their nasal organs look normal, but scientists think the acidification may disrupt the way chemical signals travel through the neurological system. It's a new kind of LSD: lost smell disorder. More studies are needed to determine if and how LSD may affect fish communities worldwide.

Complex, pH-regulated interactions between molecules in seawater also increase or decrease sound reception. Ocean acidification pumps up the volume; if pH declines by another 0.3 unit (within the scope predicted by 2100), oceans could be 40 percent louder. Although no studies have directly linked increased noise caused by acidification with changes in animal survival, the findings raise a warning flag, because marine wildlife, especially marine mammals, depend on sound for navigation, communication, hunting and courtship. *—M.J.H. and C.S.*

CLOWNFISH

in the Southern Ocean, which encircles Antarctica. Because of its cold temperatures and unique circulation patterns, the Southern Ocean will start dissolving shell and skeletal structures sooner than other oceans. It is far easier to prevent further acidification than to reverse changes once they occur; natural buffering systems would need hundreds to thousands of years to restore pH to preindustrial levels.

What can be done? For a start, the Obama administration should enact a National Ocean Policy—the first ever for the U.S.—because it could effectively coordinate action to combat these multiple threats. The U.S. Environmental Protection Agency should move forward with including CO_2 as a pollutant under the Clean Water Act, giving states authority to enforce CO_2 emissions limits. Establishing marine protected areas would allow species to recover from overexploitation; higher numbers would give their populations and gene pools more resilience in responding to climate changes. Adjusting fishery catch limits so they meet scientific recommendations rather than political desires would help. And signing the United Nations Convention on the Law of the Sea, which the U.S. has put off for decades, would make the nation a leader in marine stewardship.

More science is needed, too. Funding to support research initiatives by the European Project on Ocean Acidification and to implement the Federal Ocean Acidification Research and Monitoring Act will deepen understanding of acidification's effects. But a dramatically scaled-up monitoring network to detect acidification is also required. An international team, led by Richard Feely of the Pacific Marine Environmental Laboratory in Seattle and Victoria J. Fabry of California State University, San Marcos, has created a blueprint for integrating acidification monitoring into existing ocean tracking programs, such as OceanSITES, and the recommendations should be followed as soon as possible. In addition, expanding efforts to combine field data with laboratory experiments, such as the California Current Ecosystem Interdisciplinary Biogeochemical Moorings project, will ensure that scientists' experiments simulate realistic conditions.

Ultimately, the solution to ocean acidification lies in a new energy economy. In light of recent lethal coal mine and offshore drilling explosions and the catastrophic Gulf of Mexico oil spill, the U.S. has more reason than ever to forge a safer energy strategy for the planet. Only a dramatic reduction in fossil fuel use can prevent further CO_2 emissions from contaminating the seas. An explicit plan to shift from finite, dangerous energy sources to renewable, clean energy sources offers nations a more secure path forward. And it offers the planet, especially the oceans, a chance for a healthy future. ■

GEORGETTE DOUWMA *Nature Picture Library*

MORE TO EXPLORE

The Dangers of Ocean Acidification. Scott C. Doney in *Scientific American,* Vol. 294, No. 3, pages 58–65; March 2006.

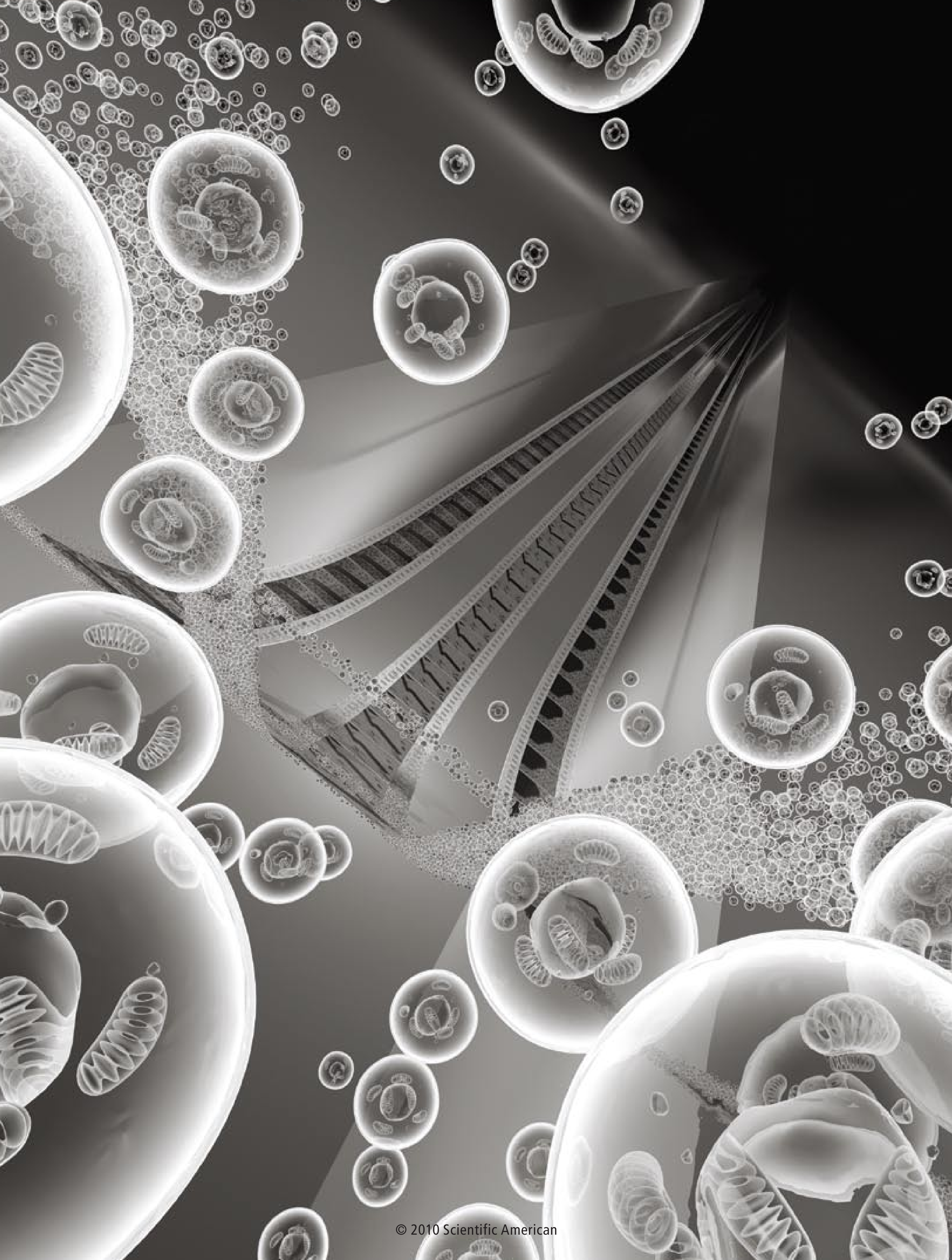
Impacts of Ocean Acidification on Marine Fauna and Ecosystem Processes. Victoria J. Fabry et al. in *ICES Journal of Marine Science,* Vol. 65, No. 3, pages 414–432; April 2008.

European Project on OCean Acidification: **www.epoca-project.eu**

For more research and policy considerations, see the Ocean Acidification Network (**www.oceanacidification.net**), notably the Monaco Declaration, and the Research Priorities Report of the Ocean in a High CO_2 World II Symposium.

U.S. Ocean Carbon and Biogeochemistry program FAQ: **www.whoi.edu/OCB-OA/FAQs**

Comment on this article at **www.ScientificAmerican.com/sciammag/aug2010**



BRYAN CHRISTIE DESIGN

FILMING THE INVISIBLE IN 4-D

Picture this: a movie revealing the inner workings of a cell or showing a nanomachine in action. A new microscopy is making such imaging possible

BY AHMED H. ZEWAIL

THE HUMAN EYE is limited in its vision. We cannot see objects much thinner than a human hair (a fraction of a millimeter) or resolve motions quicker than a blink (a tenth of a second). Advances in optics and microscopy over the past millennium have, of course, let us peer far beyond the limits of the naked eye, to view exquisite images such as a micrograph of a virus or a stroboscopic photograph of a bullet at the millisecond it punched through a lightbulb. But if we were shown a movie depicting atoms jiggling around, until recently we could be reasonably sure we were looking at a cartoon, an artist's impression or a simulation of some sort.

In the past 10 years my research group at the California Institute of Technology has developed a new form of imaging, unveiling motions that occur at the size scale of atoms and over time intervals as short as a femtosecond (a million billionth of a second). Because the technique enables imaging in both space and time and is based on the venerable electron microscope, I dubbed it four-dimensional (4-D) electron microscopy. We have used it to visualize phenomena such as the vibration of cantilevers a few billionths of a meter wide, the motion of sheets of carbon atoms in graphite vibrating like a drum after being "struck" by a laser pulse, and the transformation of matter from one state to another. We have also imaged individual proteins and cells.

Four-dimensional electron microscopy promises to answer questions in fields ranging from materials science to biology: how to understand the behavior of materials from the bottom up, from the atomic to macroscopic scale; how nanoscale or microscale machines (NEMS and MEMS) function; and how

KEY CONCEPTS

- Four-dimensional electron microscopy produces "movies" of nanoscale processes occurring over time intervals as short as femtoseconds (10^{-15} second).
- The technique builds up each frame of the movie from thousands of individual shots taken at precisely defined times.
- It has applications in a wide range of fields, including materials science, nanotechnology and medicine.

—The Editors

proteins or assemblies of biological molecules fold and become organized into larger structures, a vital process in the functioning of all living cells. Four-dimensional microscopy can also reveal the atomic arrangements of nanoscale structures (which determine the properties of new nanomaterials), and, potentially, track electrons moving around in atoms and molecules on the timescale of attoseconds (a billion billionth of a second). Along with the advances in basic science, the potential applications are wide-ranging, including the design of nanomachines and new kinds of medicines.

CATS AND ATOMS IN MOTION

ALTHOUGH 4-D MICROSCOPY is a cutting-edge technique that relies on advanced lasers and concepts from quantum physics, many of its principles can be understood by considering how scientists developed stop-motion photography more than a century ago. In particular, in the 1890s, Étienne-Jules Marey, a professor at the Collège de France, studied fast motions by placing a rotating disk with slits in it between the moving object and a photographic plate or strip, producing a series of exposures similar to modern motion picture filming.

Among other studies, Marey investigated how a falling cat rights itself so that it lands on its feet. With nothing but air to push on, how did cats instinctively perform this acrobatic feat without violating Newton's laws of motion? The fall and the flurry of legs took less than a second—too fast for the unaided eye to see precisely what happened. Marey's stop-motion snapshots provided the answer, which involves twisting the hindquarters and forequarters in opposite directions with legs extended and retracted. High divers, dancers and astronauts learn similar motions to turn themselves.

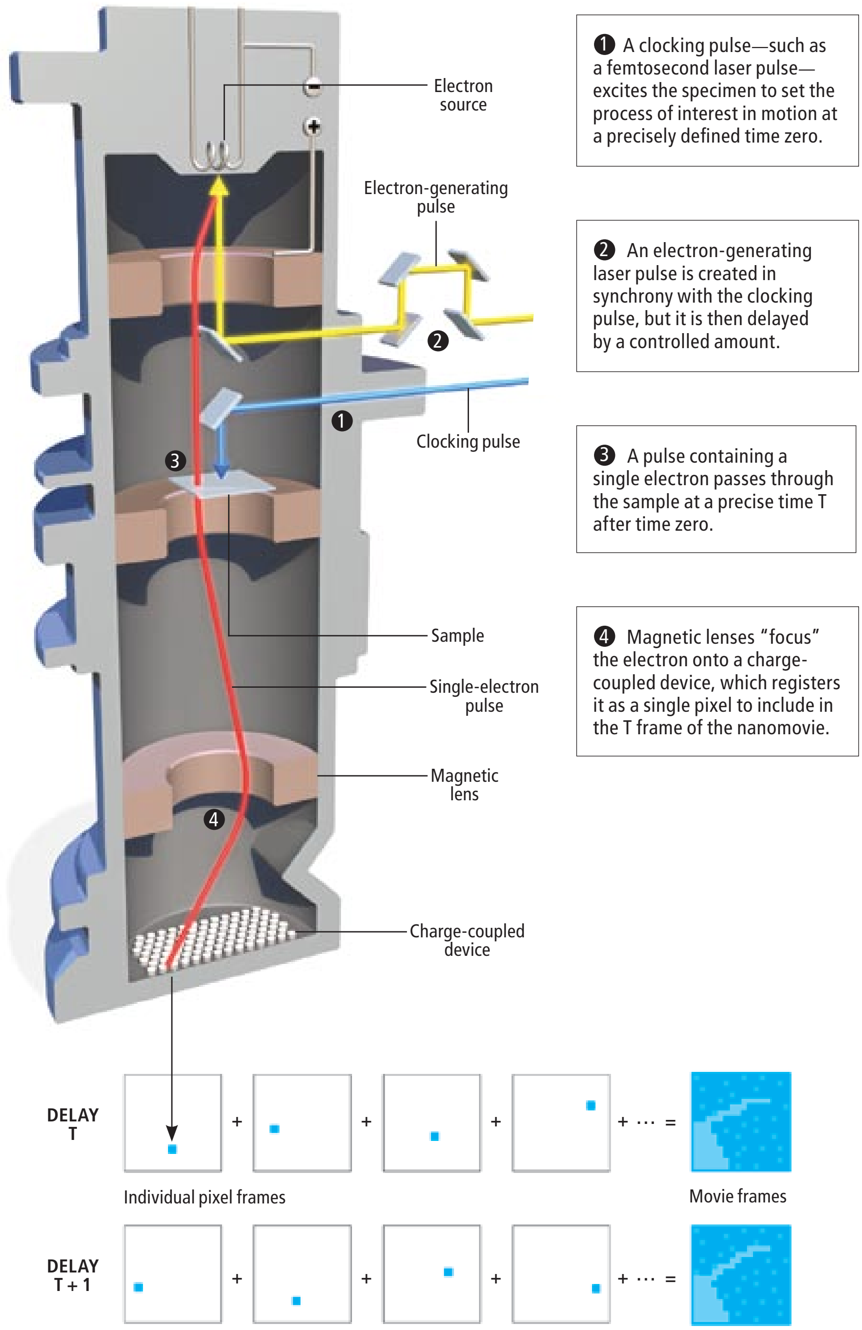
Another approach, stroboscopic photography, relied on short light flashes to capture events occurring on much shorter timescales than is possible with mechanical shutters. The flashes make an object moving in the dark momentarily visible to a detector such as an observer's eye or a photographic plate. In the mid-20th century Harold Edgerton of the Massachusetts Institute of Technology greatly advanced stroboscopic photography by developing electronics that could produce reliable, repetitive, microsecond flashes of light.

The falling-cat experiment requires shutter times or stroboscopic flashes short enough for the photographs to show the animal clearly despite its motion. Suppose the cat has righted itself

[HOW IT WORKS]

THE FOUR-DIMENSIONAL ELECTRON MICROSCOPE

A standard electron microscope records still images of a nanoscopic sample by sending a beam of electrons through the sample and focusing it onto a detector. By employing single-electron pulses, a four-dimensional electron microscope produces movie frames representing time steps as short as femtoseconds (10^{-15} second).



▲ Each frame of the nanomovie is built up by repeating this process thousands of times with the same delay and combining all the pixels from the individual shots. Researchers may also use the microscope in other modes, such as with one many-electron pulse per frame, depending on the kind of movie to be obtained. The single-electron mode produces the finest spatial resolution and captures the shortest time spans in each frame.

half a second after being released. At that instant the cat will be falling at five meters per second, so by using one-millisecond flashes we will ensure that the cat falls no more than five millimeters during each exposure so that the image of the cat will be only slightly blurred by its motion. To slice the acrobatics into 10 snapshots, the photographs must be taken every 50 milliseconds.

If we wish to observe the behavior of a molecule instead of a feline, how fast must our stroboscopic flashes be? Many changes in molecular or material structure involve atoms moving a few angstroms (one angstrom equals 10^{-10} meter). To map out such motion requires a spatial resolution of less than one angstrom. Atoms often move at speeds of about one kilometer per second in these transformations, requiring stroboscopic flashes no longer than 10 femtoseconds to observe them with better than 0.1-angstrom definition. As long ago as the 1980s researchers used femtosecond laser pulses to time chemical processes involving moving atoms, but without imaging the positions of the atoms in space—the wavelength of the light is hundreds of times longer than the spacing between atoms in molecules or materials [see "The Birth of Molecules," by Ahmed H. Zewail; Scientific American, December 1990].

Accelerated electrons have long produced images at atomic scales—as in electron microscopes—but only with targets fixed in place and imaged over time intervals of milliseconds or longer, being limited by the speed of the camera. The atom-scale movies we sought thus required the spatial resolution of an electron microscope but with femtosecond electron pulses to "illuminate" the targets. The illuminating packets of electrons are called probe pulses.

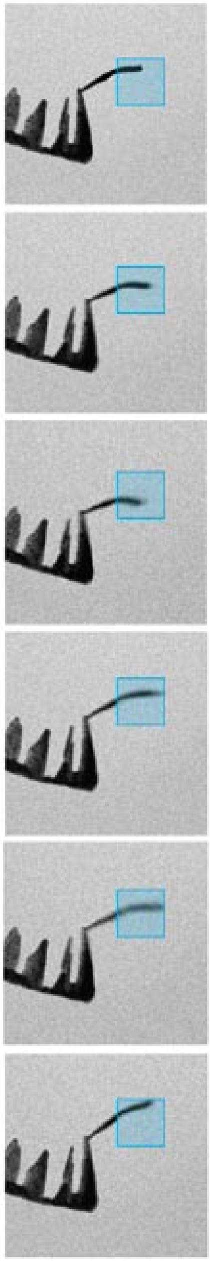
Another issue is clocking of the motion—having a well-defined instant in time when the motion begins. We will not get useful images if all the probe pulses take snapshots before the motion starts or after it finishes. In photographing the cat, the recording begins when the cat is released. For ultrafast recording, a femtosecond initiation pulse called the clocking pulse launches the material or the process to be studied.

Even with probing and clocking under control, the issue of synchronization remains. Here the typical ultrafast experiment drastically departs from the cat analogy. Marey could complete his experiment by dropping one cat once, if everything went according to plan. And it did not matter much if the series of exposures began, say, five, 10 or 17 milliseconds after the cat's release. Ultrafast microscopy, however, may probe millions of atoms or molecules for each clocking pulse or may build up images by repeating an experiment thousands of times. Imagine if Marey had been restricted to capturing only a narrow vertical strip of the field of view with each cat drop. To build up the series of full snapshots of the falling cat, he would have had to repeat the experiment many times, recording along a slightly different vertical strip each time. For the various strips to combine sensibly and form a meaningful whole image, he would need to prepare the cat in the same starting configuration for each drop and carefully synchronize the release with the shutter openings in the same way each time. (The technique would also rely on the cat moving in the same fashion every time. I suspect molecules are more reliable than cats in that respect.)

The starting configurations must be accurate to a small fraction of the cat's size, and the time synchronization must be accurate to less than the shutter durations. Similarly, in ultrafast imaging of atoms or molecules, the launch configuration must be defined to subangstrom resolution, and the relative timing of clocking and probe pulses must be of femtosecond precision. The timing of probe pulses relative to the clocking is accomplished by sending either of these pulses along a path with an adjustable length. For a pulse traveling at the speed of light, setting the path length to an accuracy of one micron corresponds to setting the relative timing with 3.3-femtosecond accuracy.

A further major and fundamental problem remained to be overcome before we could make movies with electrons. Unlike photons, electrons are charged and repel one another. Crowding a lot of them into a pulse spoils both the temporal and spatial resolutions because the electrons' mutual repulsion blows the pulse apart. In the 1980s Oleg Bostanjoglo of the Technical University of Berlin did achieve imaging using pulses having as few as 100 million electrons, but the resolutions were no better than nanoseconds and microns (later significantly improved to the submicron level by researchers at Lawrence Livermore National Laboratory).

My group attacked this challenge by developing single-electron imaging, which built on our earlier work with ultrafast electron diffraction. Each probe pulse contains a single electron and thus provides only a single "speck of light" in the final movie. Yet thanks to each pulse's careful timing and another property known as the coherence of the pulse, the many specks add up to form a useful image of the object. A similar feat



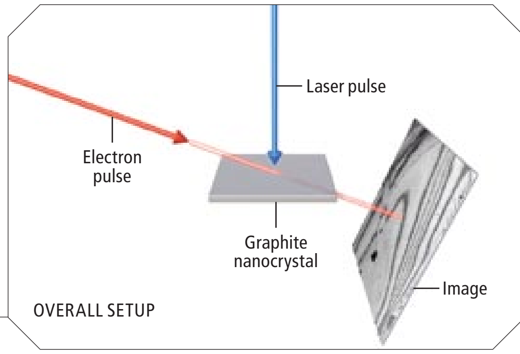
▲ A 50-nanometer-wide cantilever made of a nickel-titanium alloy oscillates after a laser pulse excites it. Blue boxes highlight the movement. The full movie (online at **ScientificAmerican.com/aug2010/nanomovies**) has one frame every 10 nanoseconds. Material properties determined from these oscillations would influence the design of nanomechanical devices.

GEORGE RETSECK (*illustrations*); COURTESY OF CALIFORNIA INSTITUTE OF TECHNOLOGY (*movie frames*)

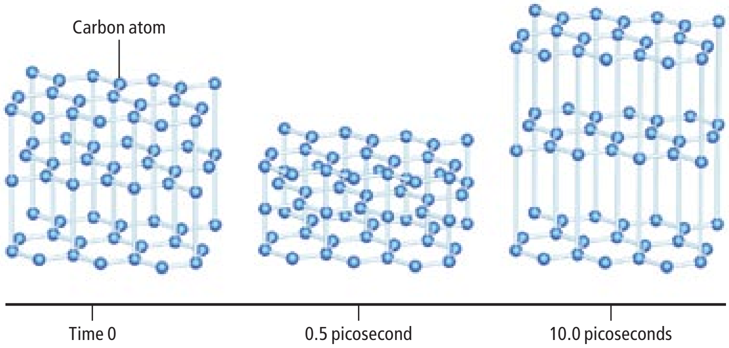
[CASE STUDY]

A NANOSCOPIC ROSETTA STONE

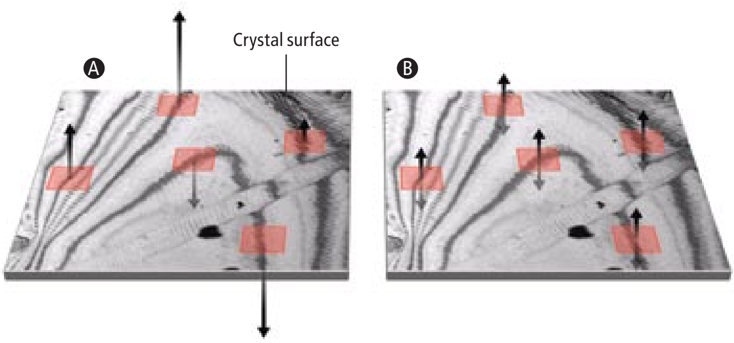
Four-dimensional microscopy of graphite nanocrystals, some only a few atomic layers thick, demonstrated three different imaging modes, producing data about the material in a variety of "languages." The studies examined how the nanocrystals responded when a laser pulse slammed into them from above.



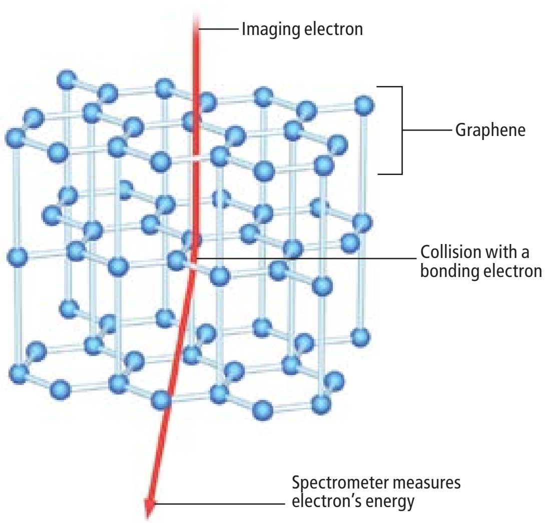
❶ Diffraction patterns revealed the motion of each crystal's atomic layers as they were pushed together and then rebounded in the picoseconds after the laser struck at time zero and as they subsequently oscillated up and down for hundreds of picoseconds.

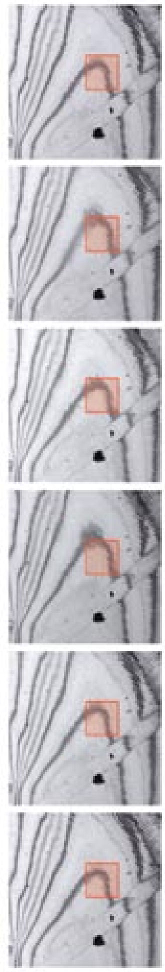


❷ Images of the nanocrystal measured these oscillations as they proceeded at different locations. Over tens of microseconds, the crystal's initially chaotic motion Ⓐ (*suggested here by arrows*) evolved into a coordinated drumming motion of the entire crystal Ⓑ.



❸ Measurements of the energy lost by imaging electrons in collisions (*depicted here*) with the graphite's electrons indicated how the carbon bonds in the material became more like the bonds in diamond during compression of the layers and more like the bonds in graphene (an isolated layer of carbon atoms) during expansion.





▲ Movie frames show the graphite nanocrystal oscillating like a drumhead after being struck by a laser pulse. The frames show a 24-micron-wide area at 250-nanosecond intervals (every fifth frame of the movie). Subtle permanent buckling of the graphite surface produces the dark bands, which move when the surface ripples. Red boxes have been added to guide the eye. The movie is online at **ScientificAmerican.com/aug2010/nanomovies**

GEORGE RETSECK (*illustrations*); COURTESY OF CALIFORNIA INSTITUTE OF TECHNOLOGY (*movie frames*) is sometimes exhibited as one of the characteristic oddities of quantum mechanics: electrons pass through two slits one at a time, each one contributing a single speck at some random location on a detection screen. Yet all the specks add up to form predictable patterns of light and darkness characteristic of interfering waves.

Single-electron imaging was the key to 4-D ultrafast electron microscopy (UEM). We could now make movies of molecules and materials as they responded to various situations, like so many startled cats twisting in the air.

DECIPHERING NANOMATTER

ONE OF OUR FIRST TARGETS was graphite, the "lead" material in pencils. We chose graphite in part because it is an unusual material, with applications in environments as extreme as those in nuclear reactor cores, and because it has close relatives that are just as remarkable. Graphite consists of carbon atoms arranged in a hexagonal pattern to form sheets reminiscent of chicken wire. Relatively weak bonds hold the sheets together in a stack. Writing with an ordinary pencil relies on pieces of the graphite sloughing off and adhering to the paper. The pencil marks include tiny quantities of the strongest material known to science—graphene, which consists of isolated single sheets of carbon atoms. Researchers are studying graphene vigorously for a variety of electronics applications. Furthermore, when soft graphite is subjected to extreme pressure, its atoms rearrange to form diamond, one of the hardest known substances.

To study graphite's response to mechanical shocks, we took nanoscale crystals of the substance—some only nanometers thick, or a few sheets of atoms—and struck them with intense femtosecond laser pulses, which served as the clocking pulses for our microscope. Each laser pulse pushed the graphite's layers of atoms momentarily closer together, setting them oscillating up and down [*see box on opposite page*]. Our electron microscope sent its electrons through these oscillating graphite layers to produce two kinds of picture: a real-space image (much like a photograph of the graphite surface) or a diffraction pattern, which is a regular array of spots whose precise configuration provides information about the arrangement and separations of atoms in the graphite lattice. In particular, we could track the layers oscillating up and down by the movements of the spots in the diffraction pattern. The oscillations had frequencies of about 10 to 100 gigahertz (10^{10} to 10^{11} cycles per second). No imaging experiment had previously observed such high-frequency resonances unfolding over time.

From our measurements we determined the elasticity of graphite perpendicular to the planes of atoms—how the material responds to compressing or stretching forces acting in that direction. Imagine that the graphite crystal is a stack of rigid metal plates connected by springs and that the laser pulse is a large sledgehammer striking the top plate. We measured the properties of the springs.

The metal-plate analogy is reasonable as long as our "camera" is zoomed in very close. If the camera figuratively "pulls back," however, more of the tiny graphite crystal comes into view. Now the hammer is striking one region of the top metal sheet, and it becomes apparent that the sheets are flexing, with the compression and expansion propagating out from the impact point in waves.

When we pull back the camera even farther and take images more slowly, yet another kind of dynamics comes into view. Now we see how the laser pulse sets the entire nanoscopically thin crystal oscillating, like a drumhead hit by a drumstick. We saw that in the first few microseconds after the laser pulse hit, the crystal's motion appeared chaotic, but as time went on the entire crystal settled down into a well-defined resonant oscillation—it drummed!

For these oscillations, the material property that sets the resonance frequency is the elasticity of the graphite planes—their response to being stretched or compressed in the plane. We found that the graphite is much more resistant to being deformed in the planes of carbon atoms than it is to having those planes pulled apart or pushed together. The results can be explained by considering that the chemical bonds joining the carbon atoms in each hexagonal layer are much stronger than the bonds linking adjacent planes to one another.

Although studies of bulk samples of graphite produce similar data about graphite's elasticity, the information we obtained tells us much more. It addresses questions of two types that are fundamental to our understanding of how materials behave at the nanoscale: first, at what length scale does the description of a substance in terms of a continuum material with properties such as elasticity break down? Second, can we extrapolate from the behavior at atomic scales of length and time to reproduce the known macroscopic properties of a material? With graphite, we found that even quite nanoscopic samples (only

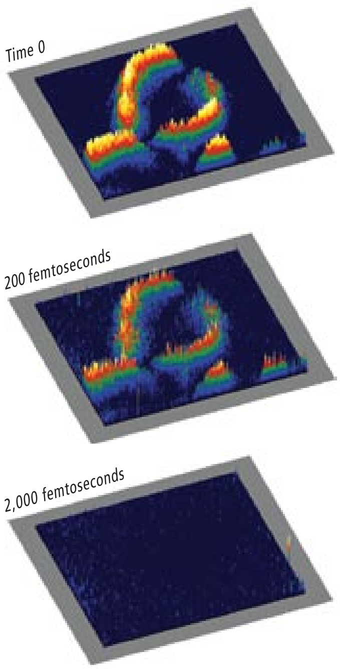
By integrating the fourth dimension, we are turning still pictures into the movies needed to watch matter's behavior—from atoms to cells—unfolding in time.

[THE AUTHOR]

COURTESY OF AZ FOUNDATION

AHMED H. ZEWAIL received the 1999 Nobel Prize in Chemistry for his studies of the transition states of chemical reactions using femtosecond spectroscopy. He is Linus Pauling Chair professor of chemistry, director of the Physical Biology Center for Ultrafast Science and Technology, and professor of physics, all at the California Institute of Technology. In 2009 he was appointed to the President's Council of Advisors on Science and Technology and was named the first U.S. Science Envoy to the Middle East.

This technique has produced images of bacterial cell membranes and protein vesicles with femtosecond- and nanometer-scale resolutions.



▲ An *Escherichia coli* bacterium was imaged with photon-induced near-field electron microscopy. A femtosecond laser pulse generated an evanescent electromagnetic field in the cell's membrane at time zero. By collecting only the imaging electrons that gained energy from this field, the technique produces high-contrast, high-spatial resolution of the membrane (*top*). The false-color contour plot depicts the intensity recorded. The method can capture events occurring on very short timescales, as is evinced by the field's significant decay after 200 femtoseconds (*middle*). The field vanishes by 2,000 femtoseconds (*bottom*).

COURTESY OF CALIFORNIA INSTITUTE OF TECHNOLOGY

a few dozen atomic layers thick) behave surprisingly like the bulk material. Would this description still be valid near the graphene limit?

The movies of graphite I have described thus far all relied on collisions of our probe electrons with the sample in which they lose no energy—like rubber balls bouncing off something hard. Sometimes, however, a probe electron may lose energy, by exciting an electron in a carbon atom. The amount of energy lost depends on the kind of bond in which the atom's electron was involved. A very old technique called electron energy loss spectroscopy can measure such losses; the energy spectra obtained provide information about the bonding in a material and the chemical elements that compose it. Using this method with our ultrafast electron microscope, we showed that during the compression phase, the bonding inside the graphite shifted toward the kind of bond that is characteristic of diamond. In the expansion phase, the bonding of the surface atoms shifted toward that of graphene. Conventional electron energy loss spectroscopy is far too slow to observe these changes.

FROM CANTILEVERS TO CELLS

MY GROUP HAS NOW carried out four-dimensional microscopy on a number of materials in addition to graphite. In iron, we made diffraction images to follow the crystal structure changing from what is called body-centered cubic to face-centered cubic, a process that occurs in many industrial applications at high temperatures, including production of steel. We saw two dynamic processes unfold when we heated the iron from room temperature to nearly 1,500 kelvins in about a nanosecond. First, specks of the face-centered phase developed, or nucleated, at locations in the crystal relatively slowly—on a nanosecond timescale—out of the incoherent motions of iron atoms. Second, these regions of the new phase grew at the speed of sound, meaning that the process took only picoseconds (10^{-12} second) to encompass the hot iron. This rapidly spreading transformation involves numerous atoms being displaced in a coordinated fashion, a curious kind of "emergence" of a large-scale change in the crystal from the innumerable underlying nanoscopic motions. Understanding of this phenomenon might lead to better ways to handle iron and steel (and many other materials) in industrial processes.

One of the most powerful applications of 4-D ultrafast electron microscopy is seeing nanosystems and microsystems as they function in real time. For instance, we imaged the resonant oscillations of nanoscopic cantilevers, which had not been accomplished before for such high-frequency motions. From our results we determined a range of quantities that describe the cantilevers' material properties and their motion, and we saw that they functioned coherently for nearly 10^{11} oscillations. Researchers can use such data to test the theoretical models that guide design of microelectromechanical and nanoelectromechanical systems, which in turn may lead to new kinds of such devices or new uses for them.

Four-dimensional imaging with ultrafast electron microscopy also has potential biological applications. To fully understand how the body functions, investigators need to know not only the structures of the various proteins and other molecular and cellular structures involved but also their dynamics—how a protein folds, how it selectively recognizes other molecules, what role the water around it plays, and so on. Some biological functions involve ultrafast steps. For instance, our vision and photosynthesis in plants both rely on photons of light triggering femtosecond-scale processes. Although many proteins function, and malfunction, on timescales much longer than femtoseconds, the atomic and molecular motions in the initial femtoseconds can determine whether these macromolecules ultimately fold properly into a useful structure or into one that, say, causes Alzheimer's disease.

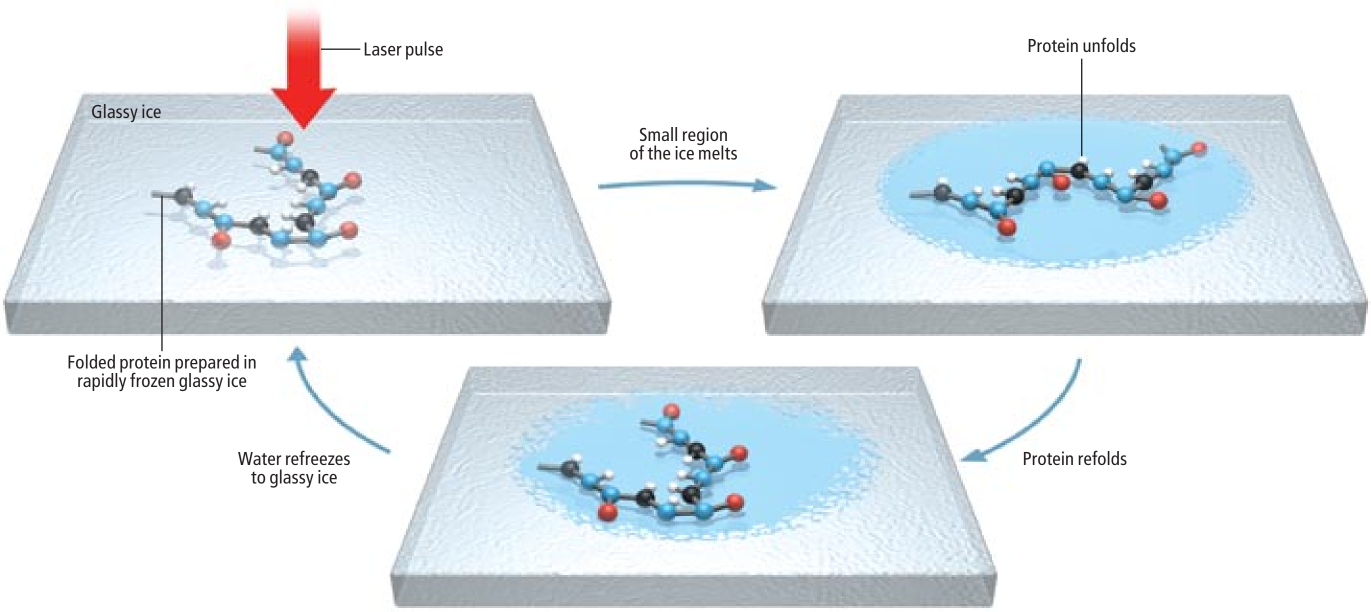
One study on protein folding illustrates the kind of techniques needed and the results that are possible. My colleagues and I investigated how quickly a short length of protein would fold into one turn of a helix by heating the water in which the protein was immersed—a so-called ultrafast temperature jump. (Helices occur in innumerable proteins.) We found that short helices formed more than 1,000 times faster than researchers have thought—arising in hundreds of picoseconds to a few nanoseconds rather than the microseconds commonly believed. Knowing that such rapid folding occurs may lead to new understanding of biochemical processes, including those involved in diseases.

Biological imaging with our 4-D ultrafast technology often relies on a well-established technique called cryoelectron microscopy, in which a sample in water is plunged quickly into liquid ethane (which boils at –89 degrees Celsius). The water freezes into a glassy solid that does not diffract electrons and spoil imaging (and the sample itself!) as ordinary ice crystals do. We have obtained images of bacterial cells and

[FUTURE WORK]

WATCHING BIOLOGY'S CLOCKWORK

By adapting a technique called cryoimaging, researchers plan to do four-dimensional microscopy of biological processes such as proteins folding. A glassy (noncrystalline) ice will hold the protein. For each shot of the movie, a laser pulse will melt the ice around the sample, causing the protein to unfold in the warm water. The movie will record the protein refolding before the water cools and refreezes. The protein could be anchored to the substrate to keep it in the same position for each shot.



GEORGE RETSECK

protein crystals in this way. In the future we hope to watch proteins embedded in such vitreous water fold and unfold: a clocking pulse will boost the temperature enough to melt a tiny droplet of the water around the protein, which will unfold and then promptly refold. When the water cools and refreezes, it renders the molecule ready for another clocking pulse. The same approach could allow us to visualize the dynamics of bacterial flagella and of the fatty acid bilayers that make up cell membranes. As with our graphite studies, ultrafast electron energy loss spectroscopy should let us map changes in bonding. Capturing the image before the biosystem moves or disintegrates should provide sharper images than currently possible in cryomicroscopy.

Variants of ultrafast electron microscopy might well push below the nanoscale in structural dynamics studies and below a femtosecond in the imaging of the electron distribution in matter. Very recently, my Caltech group demonstrated two new techniques. In one, convergent-beam UEM, the electron pulse is focused and probes only a single nanoscopic site in a specimen. The other, near-field UEM, enables imaging of the evanescent electromagnetic waves ("plasmons") created in nanoscopic structures by an intense laser pulse—a phenomenon that underlies an exciting new technology known as plasmonics [see "The Promise of Plasmonics," by Harry A. Atwater; Scientific American, April 2007]. This technique has produced images of bacterial cell membranes and protein vesicles with femtosecond- and nanometer-scale resolution.

In recent years Ferenc Krausz of Ludwig Maximilian University of Munich, Paul Corkum of the University of Ottawa and others have opened up the attosecond regime to optical (light-based) studies using extremely short laser pulses. At Caltech, we have proposed several ultrafast electron microscopy schemes for attosecond-scale electron-based imaging, and we are now pursuing the experimental realization in collaboration with Herman Batelaan of the University of Nebraska–Lincoln.

The electron microscope is extraordinarily powerful and versatile. It can operate in three distinct domains: real-space images, diffraction patterns and energy spectra. It is used in applications ranging from materials and mineralogy to nanotechnology and biology, elucidating static structures in tremendous detail. By integrating the fourth dimension, we are turning still pictures into the movies needed to watch matter's behavior—from atoms to cells—unfolding in time. ■

MORE TO EXPLORE

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Microscopy: Photons and Electrons Team Up. F. Javier García de Abajo in *Nature,* Vol. 462, page 861; December 17, 2009.

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The Hacker in Your Hardware

As if software viruses weren't bad enough, the microchips that power every aspect of our digital world are vulnerable to tampering in the factory. The consequences could be dire

BY JOHN VILLASENOR

KEY CONCEPTS

- Integrated circuits are increasingly complex and capable—but also increasingly vulnerable to attack.
- The circuits typically include designs from many sources. A "Trojan" attack hidden in one of these designs could surface long after the circuit has left the factory.
- A few relatively simple measures could go a long way toward protecting hardware from malicious hackers.

—The Editors

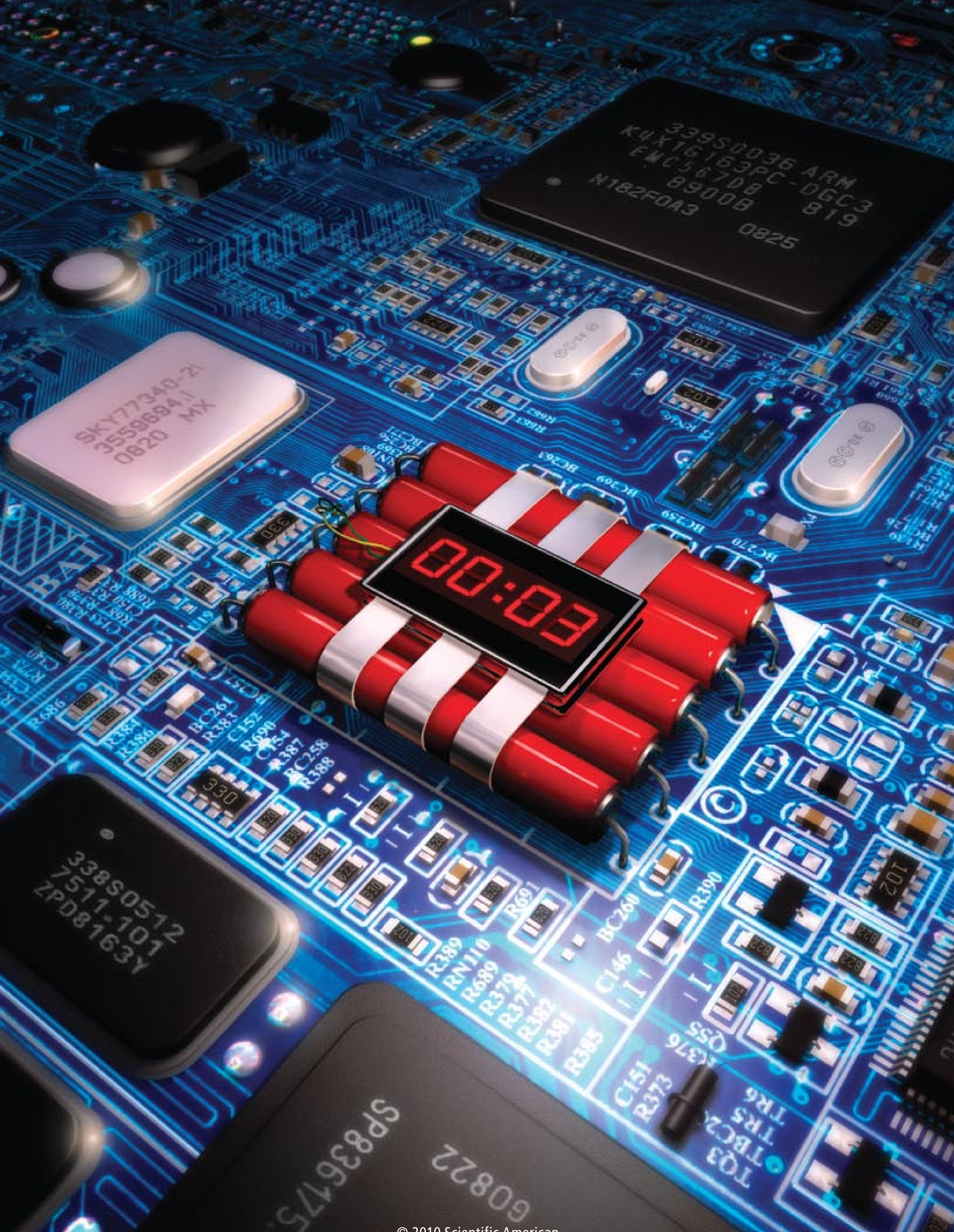
YOUR ONCE RELIABLE MOBILE phone suddenly freezes. The keypad no longer functions, and it cannot make or receive calls or text messages. You try to power off, but nothing happens. You remove the battery and reinsert it; the phone simply returns to its frozen state. Clearly, this is no ordinary glitch. Hours later you learn that yours is not an isolated problem: millions of other people also saw their phones suddenly, inexplicably, freeze.

This is one possible way that we might experience a large-scale hardware attack—one that is rooted in the increasingly sophisticated integrated circuits that serve as the brains of many of the devices we rely on every day. These circuits have become so complex that no single set of engineers can understand every piece of their design; instead teams of engineers on far-flung continents design parts of the chip, and it all comes together for the first time when the chip is printed onto silicon. The circuitry is so complex that exhaustive testing is impossible. Any bug placed in the chip's code will go unnoticed until it is activated by some sort of trigger, such as a specific date and time—like the Trojan horse, it initiates its attack after it is safely inside the guts of the hardware.

The physical nature of hardware attacks makes them potentially more problematic than worms, viruses and other malicious software. A virus can jump from machine to machine, but it can also in principle be wiped clean from any system it infects. In contrast, there is no fix for a hardware attack short of replacing the infected units. At least, not yet.

The difficulty of fixing a systemic, malicious hardware problem keeps cybersecurity experts up at night. Anything that uses a microprocessor—which is to say, just about everything electronic—is vulnerable. Integrated circuits lie at the heart of our communications systems and the world's electricity supply. They position the

KENN BROWN *Mondolithic Studios*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flaps on modern airliners and modulate the power in your car's antilock braking system. They are used to access bank vaults and ATMs and to run the stock market. They form the core of almost every critical system in use by our armed forces. A well-designed attack could conceivably bring commerce to a halt or immobilize critical parts of our military or government.

Because Trojan hardware can hide for years before it is activated, it is possible—perhaps likely—that hardware bugs have already been planted. And although no large-scale hardware attacks have yet been confirmed, they are inevitable.

As we know all too well from combating software-based cyberattacks, a relatively small proportion of people who use their technical skills for malicious purposes can have an big impact. Thus, rather than asking whether or not hardware attacks will occur, the better questions are: What forms will these attacks take? What consequences will they have? And, perhaps most important of all, what can we do to detect and stop them or at least minimize their effects?

BLOCK BY BLOCK

AN INTEGRATED CIRCUIT, or chip, is simply an electronic circuit etched onto a single piece of a semiconductor material, most often silicon. Modern integrated circuits are physically quite small—no more than a few square centimeters and often much smaller—but can contain several billion transistors. The very complexity of modern chips creates the vulnerabilities that make Trojan attacks possible.

Modern chips are divided into subunits called blocks that perform different functions. In a mobile phone's processor, for example, one block might be memory that can be used to store frames of video captured by the camera. A second block might compress that video into an MPEG file, and a third block might convert those files into a form that can be transmitted over the antenna. Data move among these blocks across a system bus, which acts like a highway connecting the different parts of the chip.

When a company embarks on the design of a new integrated circuit, it first maps out what functional blocks the circuit will need. Some of these blocks will be designed in-house, either from scratch or as a modification of a block design used in the company's earlier chips. Others will be licensed from third parties that might specialize in a certain type of functionality—receiving data from an antenna, for example.

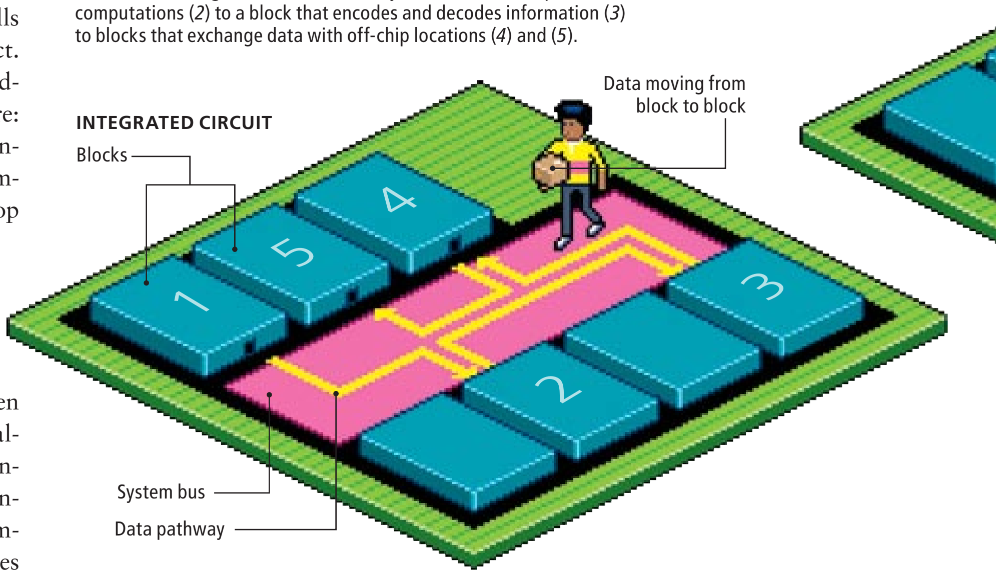
The block from the third party does not come

[CIRCUIT VULNERABILITIES]

GLOBAL SECURITY PROBLEM

A single chip can incorporate circuits designed in locations across the globe by hundreds of people working at many different firms. This globalization of chip design makes new product development faster and less expensive. It also creates risks, because it is difficult to detect rogue circuitry hidden among the hundreds of millions of transistors before the chip ships.

▼ **INSIDE AN INTEGRATED CIRCUIT:** A chip contains a set of functional blocks, each dedicated to performing a specific task. Data move from block to block across a system bus, and traffic flow in the bus is controlled by yet another block, the bus arbiter. In a cell phone, for instance, data might travel from memory (*1*) to a block that performs computations (*2*) to a block that encodes and decodes information (*3*) to blocks that exchange data with off-chip locations (*4*) and (*5*).



HARDWARE DESIGN BY THE NUMBERS

1,550
Estimated number of companies worldwide involved in integrated-circuit design, including 700 in North America, 600 in Asia, and 250 in Europe, the Middle East and Africa

2,500
The approximate number of new chips designed every year

$235 billion
Global semiconductor sales revenue in 2009

as a physical piece of silicon, because the goal in building the integrated circuit is to have all the functional blocks printed onto the same surface. Instead the block comes as a data file that fully describes how the block should be etched onto the silicon. The file can be thousands of lines long, making it a practical impossibility for a human to read the file and understand everything that is going on. The block provider will also typically supply some software that the block purchaser uses to model how the block will respond to a variety of situations. Before any circuits are printed, the lead company will join all the model blocks into a computer simulation to ensure the chip will function as expected. Only when the model passes a battery of tests will the company begin the time-consuming and expensive process of fabricating the physical integrated circuits.

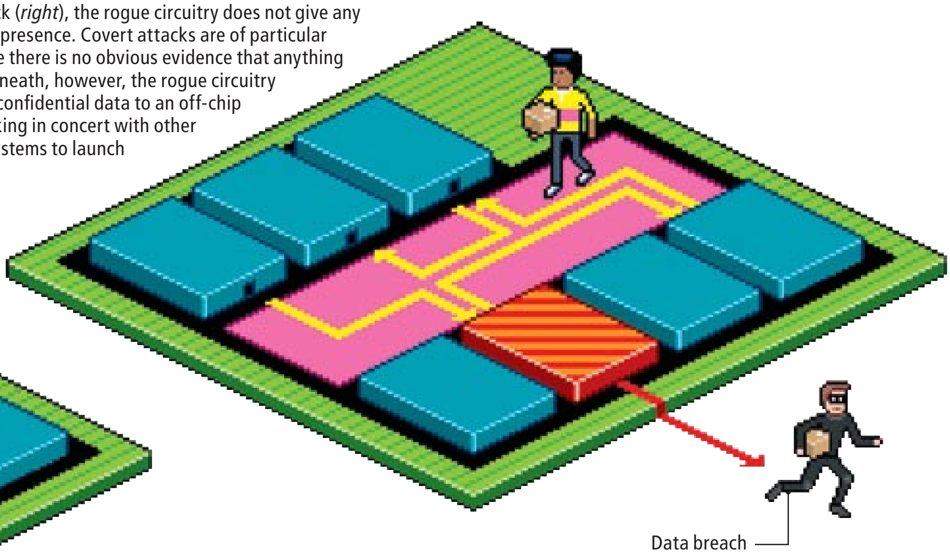
Here is where the vulnerability lies: because the rogue hardware requires a specific trigger to become active, chipmakers will have to test

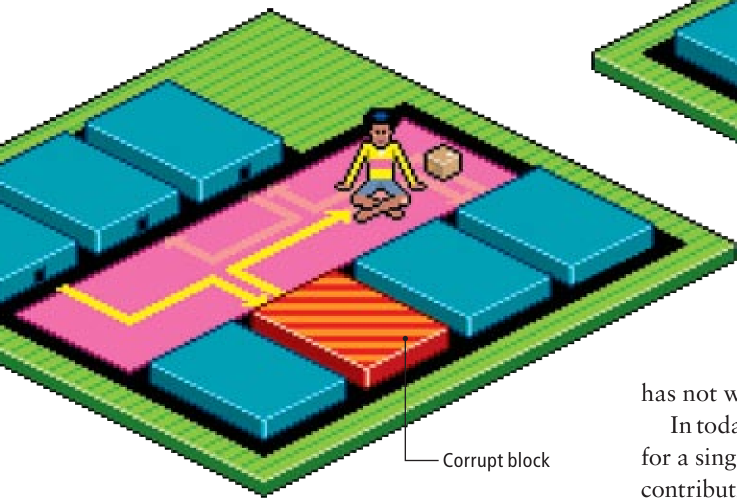
QUICKHONEY

WHEN THINGS GO WRONG: A chip containing a Trojan will function normally until the rogue hardware is awakened by a trigger and instructed to attack. Triggers could take many possible forms, including the arrival of a certain date and time or a "wake-up call" from the outside world arriving as a specially encoded packet of data. The Trojan can then execute one of two types of attacks—overt and covert.

In an overt attack (*below*), the rogue hardware stops the chip from functioning properly. In this example, a corrupted block refuses to release its access to the system bus, thereby preventing other blocks from communicating with one another. In this case, the chip would cease to function altogether.

In a covert attack (*right*), the rogue circuitry does not give any indication of its presence. Covert attacks are of particular concern because there is no obvious evidence that anything is wrong. Underneath, however, the rogue circuitry can be sending confidential data to an off-chip location or working in concert with other compromised systems to launch other attacks.





their models against every possible trigger to ensure that the hardware is clean. This is simply not possible—the universe of possible triggers is far too large. In addition to internal triggers such as a date-based trigger described in the mobile phone example, hackers could employ external triggers such as the reception of a text or e-mail message containing a specific set of characters. Companies test as best as they can, even though this necessarily means testing only a very small percentage of possible inputs. If a block behaves as expected, it is assumed to be functioning correctly.

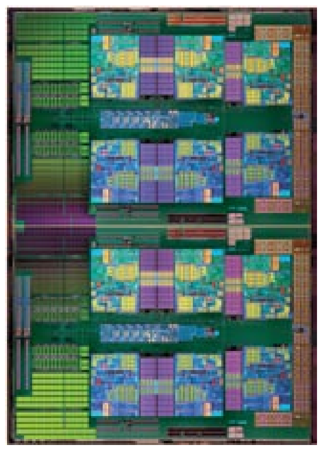
AN ISSUE OF TRUST

IN THE EARLY DAYS of integrated-circuit design, no one had to worry about hackers. The first designs were created completely in-house, executed by small teams who were working toward a common purpose. Because of this organizational security, the designers established open protocols that assumed different parts of the chip would behave as expected. (The history echoes the choices that were made in the early days of the Internet, when a small academic community built an open platform that assumed everyone would behave nicely. That assumption has not withstood the growth of the Internet.)

In today's world, however, the design process for a single, large integrated circuit can involve contributions from hundreds or even thousands of people at locations on multiple continents. As this design goes through various stages of development, portions of the design are stored on many different physical platforms and repeatedly exchanged among many parties. For example, an American manufacturer might combine designs from separate branches of the company with designs from third-party vendors in the U.S., Europe and India, then fabricate the chip in a Chinese factory. These global networks have become a fact of life in recent years, and they have provided large savings in cost and efficiency. But they make security far more complicated than back in the days when things were done in one facility. Given the sheer number of people and complexity involved in a large integrated-circuit design, there is always a risk that an unauthorized outsider might gain access and corrupt the design without detection.

A very small—but not zero—risk also exists that a design could be corrupted by someone with internal access. While the overwhelming majority of people involved in any aspect of circuit design will endeavor to deliver designs of the highest quality, as with any security issue, malicious actions taken by even a very small minority of those with inside access acting maliciously can create significant problems.

MODERN MIND: The AMD Opteron 6100 processor, shown here at actual size, is a package of two integrated circuts containing a total of more than 1.8 billion transistors. The various colors correspond to different functional blocks.



COURTESY OF AMD

[SECURITY SOLUTIONS]

HOW TO STOP HARDWARE HACKERS

A secure integrated circuit contains a modest amount of extra hardware that polices the chip from the inside. When hostile behavior is detected, a set of security measures can spring into place within microseconds to identify the source of the attack and react with countermeasures to surmount it. Here are a few strategies being developed.

SECURITY MEASURE	INTENDED EFFECT	HOW IT WORKS
Memory gatekeeper	Preempts any attempt by a rogue block to access off-limits areas of memory; the measure helps to prevent spying or data corruption	A gatekeeper ensures that blocks can access only authorized portions of memory, and flags any attempts at unauthorized access
Secure system bus	Prevents a malicious takeover of a system bus, which could result in a complete circuit shutdown or dramatically slowed operation	The bus analyzes statistical patterns of bus access by different functional blocks and flags strange behavior
Input/output monitor	Impedes covert spying—when the chip attempts to copy data to off-chip locations	The circuit analyzes the movement of data on and off the chip and compares this flow with the expected pattern, flagging any aberrations
On-site block testing	Defends against a Trojan attack that attempts to damage a formerly "healthy" block	An on-chip integrity checker occasionally tests the blocks to make sure they continue to operate as expected
Extra programmable hardware logic	Allows the circuit to quarantine a compromised block and replicate its function	The extra logic is configured to replace the quarantined functional block—though likely at a slower speed
Attack alert system	Allows other circuits to preemptively protect themselves against impending attacks	A circuit under attack institutes countermeasures and sends a warning about the attack to other devices containing the same circuit

Ideally, would-be attackers would never get the opportunity to gain access to an integrated circuit during the design and manufacturing process, thereby ensuring that hardware attacks never occur. This is the strategy that the Defense Advanced Research Projects Agency (DARPA), the research agency run by the Pentagon, has pursued with its Trust in Integrated Circuits program. DARPA is designing processes to ensure that all the steps in the design and manufacturing chain are carried out by companies and people known to be trustworthy and working in secure environments. (In addition, the agency is funding research into new ways to test chips before they are placed into U.S. weapons systems.) Yet in the real world, actions taken to secure the design process are never perfect.

Hardware designers should also build circuits that identify and respond to attacks even as they are taking place, like an onboard police force. Although a community should certainly engage in all reasonable measures to discourage potential criminals from committing crimes, any responsible community also recognizes that such efforts, no matter how well intentioned and thorough, will never be 100 percent effective. It is critical to have a police force that can respond quickly and appropriately when crimes do occur.

SECURING THE CIRCUIT

A CIRCUIT THAT can effectively detect and respond to attacks is called a secure circuit. These chips have a modest amount of extra circuitry specifically designed to look for behavior that may reveal a problem. If an attack is suspected, the secure circuit will identify the type of attack and attempt to minimize the resulting damage.

In the example of the frozen cell phone, the failure may have been caused by a single block that was acting out of order. That block interacts with all the other blocks over the system bus. This bus, in turn, has a bus arbiter—a traffic cop that decides what information can travel over the bus at what time. Yet the traffic cop analogy is not perfect. While a traffic cop can instruct traffic when to start and when to stop, a bus arbiter has less authority. It can grant permission for a block to start sending information through the bus, but the block can retain that access for as long as it wants—a vestige of the long-ago assumption that blocks would always behave properly. Herein lies the problem.

In a typical system, a block will retain access to the system bus for only as long as necessary before it relinquishes it for use by other blocks.

QUICKHONEY

The bus arbiter sees that the system bus is available and then assigns it to another block. But if a block keeps control of the bus indefinitely, no further data will be able move within the integrated circuit, and the system will freeze.

In contrast, a secure integrated circuit performs constant checks to ensure that the communications among different blocks have not been disrupted. When it detects one block monopolizing access to the bus, the secure integrated circuit can respond by quarantining the malicious block. It can then use its store of programmable logic hardware to replace the lost functionality. This process will likely slow the overall operation, but it will at least keep the device working.

An overt attack is probably not the most pernicious threat, however. A covert attack could be much worse. In a covert attack, the device appears to operate normally, but in reality it is acting with malicious intent. A mobile phone, for instance, might secretly begin to transmit a copy of all incoming and outgoing text messages to a third party. An unsuspecting observer would not notice anything wrong, and the attack could continue indefinitely.

A secure integrated circuit would provide a critically important defense against this type of attack. The chip would constantly monitor the amount and type of data moving on and off the integrated circuit and statistically compare this movement with the expected data flows. Any anomaly would be flagged as a potential data leak, and the chip would either alert the user or begin to staunch the flow on its own.

In addition to taking steps to counter the effects of a Trojan attack on its own operations, an integrated circuit can notify other devices of the type of assault, potentially allowing them to take preemptive actions to avoid it (or at least to minimize its effects). Such notification is not as far-fetched as it might seem given the level of network connectivity that almost all systems now have. For example, if a circuit experiencing an attack can identify the initiating trigger, it can alert other circuits to screen for that particular message.

The measures described here will be effective only if the parts of the circuit responsible for managing security are themselves secure and trustworthy. This might seem like a circular argument—another way of saying that the only way to secure a circuit is to secure a circuit—but the elements of the circuit devoted to security constitute only a small fraction of the overall design. They can be designed in-house to ensure that only highly trusted parties have access.

WHAT TO DO NEXT

THANKS TO the efforts of governments, academic researchers and the commercial sector, enormous progress has been made in Internet security. The same cannot be said of the state of integrated-circuit security, which lies roughly where Internet security was 15 years ago: there is growing awareness that the issue is worthy of attention, but defensive strategies have not yet been fully developed, much less put into practice.

A comprehensive approach to preventing hardware attacks requires action on several levels. Strategies that aim to ensure compromised hardware never gets out the door, such as DARPA's program, are a good start. But most important, we must begin to implement secure design measures such as the ones discussed here that can defend against attacks as they occur. These defenses will not come free. As with security in other domains, integrated-circuit security will require the expense of time, money and effort. A wide spectrum of options represents trade-offs between the effectiveness of the security and the cost of implementing it. Fortunately, it is possible to deliver effective security at modest costs.

A secure integrated circuit contains a small amount of extra logic. In research my group has conducted at the University of California, Los Angeles, we have found that the increase in integrated-circuit size is typically several percent. There is also generally a cost in operating speed, given that the steps taken to ensure that functional blocks are behaving appropriately can consume some clock cycles that might otherwise be used for core operational tasks. Again, however, we have found the speed reduction to be small in relative terms, and in some cases no speed reduction happens at all if the security measures are performed using logic and functional blocks that are temporarily dormant.

Keeping hardware secure will inevitably become an arms race requiring continual innovation to stay ahead of the latest attacks, as has been the case in the software world. Whereas new circuits cannot be downloaded over the Internet in the manner used to fix security holes identified in software, modern integrated circuits have a number of reconfigurable aspects that, with appropriate steps taken during the integrated-circuit design process, could be used to automatically replace parts of hardware that become incapacitated in the event of an attack. Engineered flexibility is our best defense.

Even if hardware attacks are inevitable, that does not mean that they have to be successful. ■

[THE AUTHOR]

COURTESY OF RORY EARNSHAW

JOHN VILLASENOR joined the electrical engineering department at the University of California, Los Angeles, in 1992. Prior to that he worked on developing methods to image the earth from space at the NASA Jet Propulsion Laboratory and completed an M.S. and Ph.D. at Stanford University. At U.C.L.A. his research focuses on the methods, technologies and systems used to capture information in the world around us, convert it into digital form, and move it efficiently and securely from one place to another.

MORE TO EXPLORE

Trojan Detection Using IC Fingerprinting. D. Agrawal et al. in *Proceedings of the 2007 IEEE Symposium on Security and Privacy.* Berkeley, Calif., May 2007.

Old Trick Threatens the Newest Weapons. John Markoff in *New York Times;* October 26, 2009.

A Trojan-Resistant System-on-Chip Bus Architecture. L. Kim, J. Villasenor and C. Koc in *Proceedings of the 2009 IEEE Military Communications Conference.* Boston, October 2009.

Securing the Information Highway. Wesley K. Clark and Peter L. Levin in *Foreign Affairs,* November/December 2009.

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Plastic Surf

Small remnants of toys, bottles and packaging have an unhealthful afterlife in the ocean

BY JENNIFER ACKERMAN ■ PHOTOGRAPH BY CARY WOLINSKY

By now even schoolchildren know that the plastics we discard every year in the millions of tons persist in the environment for hundreds of years. And we have all heard of the horrors caused by such debris in the sea: fur seals entangled by nylon nets, sea otters choking on polyethylene six-pack rings, and plastic bags or toys stuck in the guts of sea turtles. This photograph, showing plastic fragments collected in just an hour at a cove near Gloucester, Mass., hints at a lesser-known but equally disturbing story: much smaller bits of plastic that are accumulating in oceans all over the world can potentially harm marine life and possibly even human health.

Although plastic does not get digested by microbes, as food and paper are, it does slowly "photodegrade": ultraviolet light and heat from the sun increase its brittleness, causing it to weaken, crack and break up into smaller and smaller fragments. Indeed, a handful of sand or cup of seawater from nearly anywhere in the world will probably be peppered with microplastics—pieces that are tinier than a small pea and often invisible. Scientists fear the possible effects of this plastic confetti on zooplankton and other creatures at the base of the marine food web, which get consumed by larger organisms—turtles, fish, birds—and, ultimately, by us.

The bits evoke worry for several reasons. They may block the feeding appendages or digestive tracts of small invertebrates. Also, chemicals incorporated into plastic products during their manufacture can threaten health when ingested—among them the endocrine disruptor bisphenol A. Moreover, plastic debris floating in the ocean acts as a magnet and sponge for toxic substances, such as DDT, dioxins and PCBs, absorbing concentrations 100 to a million times that of surrounding seawater. Life-forms eating pollutant-loaded microplastics may therefore be exposing themselves—and those who feed on them—to concentrated poisons. A solution, many scientists agree, is designing plastic products that can be recycled throughout much of their material life. ■

Jennifer Ackerman is a science writer based in Virginia.

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SIREN CALL FOR BIRDS
Seabirds are known to pick up plastic fragments, especially red ones, mistaking them for food at the sea surface. Even in remote areas, scientists are finding birds, such as Antarctic prions and sub-Antarctic skuas, that have ingested plastic marine debris.

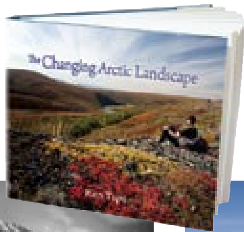
LIKE ROCKS INTO SAND
The same mechanical action of waves against shoreline that turns rocks into sand can smooth and round the edges of plastics and help to grind them into tiny fragments and even powder, but they do not disappear.

READY TO CRACK
Scientists have identified at least nine types of plastic waste in the oceans, from acrylic and nylon to polyester, polypropylene (found in ropes and containers), polycarbonate (the hard plastic in eyeglass lenses) and polystyrene (used in making Styrofoam). Polystyrene begins to break into smaller pieces within a year, and even hard plastics such as polycarbonate can come apart in the sea, potentially leaking chemicals as they do.

Arctic Change ▪ Malaria's Grip ▪ Periodic Table

BY KATE WONG

THE CHANGING ARCTIC LANDSCAPE
by Ken D. Tape. University of Alaska Press, 2010 ($35)



Photographer Ken D. Tape pairs old and new images of sites in northern Alaska to document the impact of climate change on the Arctic.

BROOKS RANGE, 1973

BROOKS RANGE, 2007

DENNIS TRABANT (*left*); KEN D. TAPE (*right*)

EXCERPT

THE FEVER: HOW MALARIA HAS RULED HUMANKIND FOR 500,000 YEARS
by Sonia Shah. Farrar, Straus and Giroux, 2010 ($26)

Every year malaria infects more than 500 million people; every 30 seconds someone dies from it. Journalist Sonia Shah examines the various factors that have allowed the disease to flourish despite scientists' best efforts to combat it. Where malaria is endemic, many people, Shah says, do not accept that the disease is transmitted solely by mosquitoes, or else they consider it largely benign. Here she describes how Malawi's dominant ethnic group, the Chewa, view it.

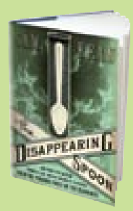
"For us, malaria is a disease caused by a protozoan parasite transmitted by mosquito. For the Lake Malombe Chewa, malaria—which the locals call *malungo,* and lump together with other malaria-like illnesses—is a disease caused by mosquitoes … and spirits and jealousy and hexes and bad weather and hard work and dirty water and rotten food, among other things.…

"Like intelligent design and other forms of magical thinking, these beliefs are not unrelated to actual shortcomings in the scientific explanations with which they compete. Every time mosquitoes bit Lake Malombe Chewa and they did not fall ill with *malungo*, their disbelief in the mosquito theory of malaria transmission strengthened. Ditto for every time they took an antimalarial drug and it failed to work. If the drug didn't work, this meant that the *malungo* was not caused by mosquitoes.

"What these beliefs mean is that while our malaria is an eminently preventable disease, for the Chewa, as for other rural peoples living traditional lives, it is anything but. Malaria is everywhere, caused by everything.…

"It isn't that the Chewa villagers don't understand that destroying mosquitoes' larval habitats, or sleeping under bed nets, or taking prophylactic drugs, or sealing up their houses, helps prevent malaria. And it isn't that they aren't interested in preventing malaria.… It is that, as with people everywhere, there's little interest in fixes that are time-consuming or temporary, or that promise only—in their minds—marginal efficacy. Even if some *malungo* can be alleviated by people avoiding mosquito bites, they can't possibly avoid exposure to the weather, or to hard work, or to the envy of their neighbors."

ALSO NOTABLE



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  by Sam Kean. Little, Brown, 2010 ($24.99)
- **The Book of Shells: A Life-Size Guide to Identifying and Classifying Six Hundred Seashells**
  by M. G. Harasewych and Fabio Moretzsohn. University of Chicago Press, 2010 ($55)
- **Voyager: Seeking Newer Worlds in the Third Great Age of Discovery**
  by Stephen J. Pyne. Viking, 2010 ($29.95)
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  by Timothy Taylor. Palgrave Macmillan, 2010 ($27)
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  by David Stipp. Current, 2010 ($26.95)
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  by Wenda Trevathan. Oxford University Press, 2010 ($34.95)
- **The Zodiac of Paris: How an Improbable Controversy over an Ancient Egyptian Artifact Provoked a Modern Debate between Religion and Science**
  by Jed Z. Buchwald and Diane Greco Josefowicz. Princeton University Press, 2010 ($35)

Take Me Out of the Ball Game

Physics and medicine are the biggest players on the diamond

BY STEVE MIRSKY

Baseball is a game of trajectories. And as Yogi Berra supposedly said, you can observe a lot just by watching. For example, at Yankee Stadium on May 29, I observed New York slugger Alex Rodriguez hit a pitch by Cleveland Indians David Huff back up the middle and off the pitcher's head. In fact, the ball hit Huff's head so hard that it rolled nearly all the way to the right-field wall. The ball, that is, not Huff's head. He collapsed in a heap and remained face down on the mound for several minutes. Huff eventually left on a stretcher. Home team fans who then watched the Yankees blow a six-run lead left in a huff.

Anyway, many in the crowd feared that Huff was seriously injured. Having observed physics teachers years earlier, however, I was guardedly optimistic—precisely because the ball had ricocheted so far and so fast. Had the ball rebounded from Huff's dome only a few feet straight back toward home plate, I would have been concerned that the poor pitcher had become the second player in major league baseball history to be killed on the job. In that scenario, much of the ball's energy of motion would have been imparted to the pitcher. But said energy appeared to have been expended on sending the ball skittering into the right-field corner, with only a small amount having been transferred to Huff's head.

Indeed, after being checked out at nearby New York–Presbyterian Hospital, Huff returned to the scene of the bean, seemingly little the worse for wear, before the game was even over. He was helped in this effort by the fact that the 13–11 Indians win took an excruciating four hours and 22 minutes, which felt much longer for those of us near the event horizon.

(The only man killed playing major league baseball is Cleveland Indians shortstop Ray Chapman, who, after being struck in the temple by a pitch from Carl Mays of the Yankees in 1920, never regained consciousness. A scant 51 years later the powers-that-were made protective headgear mandatory.)

On the same afternoon as A-Rod's double off Broca's area, a far more serious injury was sustained by Kendry Morales, first baseman for a team somehow seriously referred to as the Los Angeles Angels of Anaheim. Morales hit a game-winning grand-slam home run in the bottom of the ninth, trotted around the bases, leapt onto home plate and shattered his left ankle. He'll need surgery and could miss the rest of the season. Morales is still lucky compared with other world-class athletes that after similar injuries used to be taken out back and shot and more recently are euthanized by large-animal veterinarians.

That same evening Philadelphia Phillies pitcher Roy Halladay pitched the 20th perfect game in major league history, retiring all 27 Florida Marlins who futilely waved their tribute sticks, I mean bats, at him. The *Philadelphia Inquirer*'s Bill Lyon wrote that Halladay "made the ball dive, and he made it rise."

Lyon is hitting .500. No pitcher throwing overhand can really make the ball rise, says University of New Hampshire psychology professor Kenneth Fuld, who has taught a course called Visual Perception. (New Hampshire was where I came closest to playing professional baseball, when I was given room and board for a week so I could be a ringer on the Dartmouth College math department softball team. Given sufficient initial conditions, those guys could tell you exactly where an opponent's batted ball would land when, in keeping with math department tradition, they didn't catch it.)

According to Fuld, whose son, Sam, is an outfielder on the Chicago Cubs' 40-man roster, straight fastballs delivered overhand always drop slightly on their way to home plate. But the batter perceives the trajectory as level. An unusually fast pitch, which drops merely less than expected, will then appear to rise. It's an illusion, like when you think your stationary train is moving because a train on the next track moves or when paying six bucks for a hot dog at Yankee Stadium doesn't seem at all crazy, because you already shelled out $125 for your seat. ■

PHOTOGRAPH BY FLYNN LARSEN; ILLUSTRATION BY MATT COLLINS