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May 2011

Astronomy
Where Are the Lost Galaxies?

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Physics
String Theory's Strangest Numbers

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Radical Energy Solutions

They're risky—but they could pay off big


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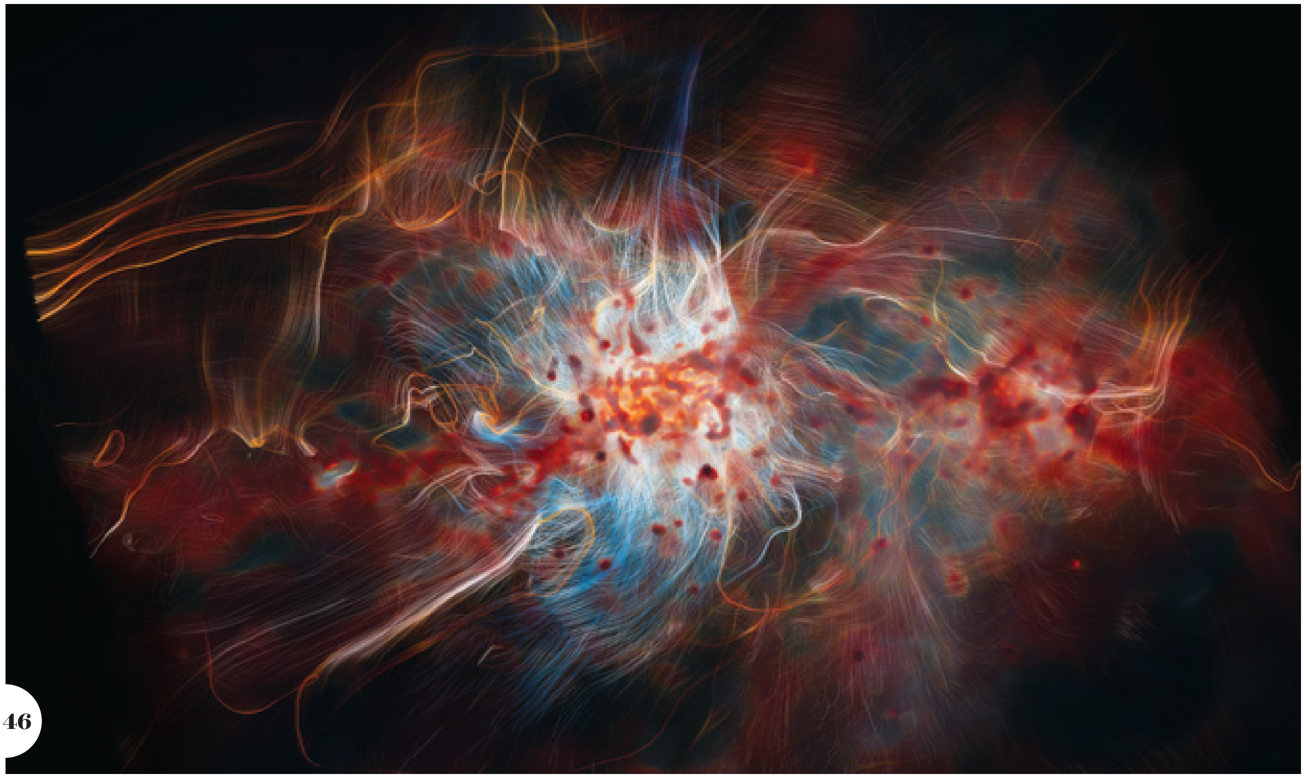
ON THE COVER

Better renewable technologies will broaden energy supply, but radical innovations are needed to fundamentally change the energy game. SCIENTIFIC AMERICAN has unearthed seven exotic technologies that may be long shots to succeed, but if they do they could significantly improve energy security and efficiency. And the prototypes are just plain fascinating. Illustration by Chris Labrooy.

SCIENTIFIC AMERICAN

May 2011 Volume 304, Number 5



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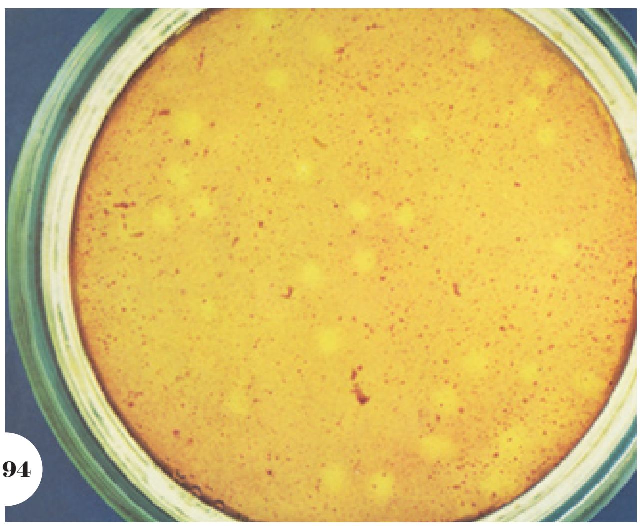

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SCIENTIFIC AMERICAN

DEPARTMENTS

ON THE WEB

50 Years of Human Spaceflight
On April 12, 1961, cosmonaut Yuri Gagarin became the first human in space. What firsts will humankind realize in the coming decades of space exploration?
Go to www.ScientificAmerican.com/may2011/spaceflight

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Mariette DiChristina is editor in chief of *Scientific American.* Find her on Twitter @SAeditorinchief

Risks vs. Gains

One of the biggest issues of our time is energy: where to get it, how to save it, and how it relates to our climate, food and water. Naturally, we cover this topic in our pages in multiple ways, and from many angles, in practically every edition. In our January issue, for instance, we ran an interview with clean technology investor Vinod Khosla, co-founder of Sun Microsystems and a member of our board of advisers ["In Search of the Radical Solution," interview by Mark Fischetti]. Khosla made a bold statement: "If an innovative idea has a 90 percent probability of failing, then I like it. Why? Because it is likely to be the one that has a quantum jump in performance." In contrast, he said, only pursuing "high-probability areas" yields results that are "all incremental."

I'm not sure I would put it that way, but we agree that big ideas are part of a portfolio of technologies to address national and global energy needs. Thus, our cover story presents "7 Radical Energy Solutions." None is probably the "ultimate" answer—in fact, they all share a high risk of failure. But they could be part of a rational combination of technologies and policies, balancing the requirements of energy security, environmental soundness and public health. The article starts on page 38.

On a personal note, we are saddened to report that one of the stories in the cover feature is the last piece we will be able to run by writer JR Minkel, whom we lost too young earlier this year. JR was a writer of great intelligence, passion and curiosity. We will try to draw inspiration and solace from his memory as we consider the challenges of the future ahead. We will need them. SA

CALLING ALL SCIENTISTS

The National Academies last fall reported that the U.S. ranks 27 out of 29 wealthy countries in proportion of college students with degrees in science or engineering. It called on federal and state governments to improve teaching in math and science by targeting early childhood education and public school curricula and by supporting teacher training in crucial subjects. But many science teachers today, particularly in middle school and younger grades, do not have a science degree.

Enter 1,000 Scientists in 1,000 Days, which aims to help teachers and scientists to connect with one another. Scientific American is launching this program as part of its three-year (that's the 1,000 days) Change the Equation initiatives with our parent company, Nature Publishing Group. The idea is simple. We seek scientists, mathematicians and engineers who are willing to volunteer to advise on curricula, answer a classroom's questions or visit a school—for instance, to participate in a lab or to talk about what you do.

Scientists, mathematicians, engineers: We hope you will consider participating in this worthy program by volunteering using the form found at www.ScientificAmerican.com.

Teachers: We plan to be ready with a geographic listing of experts near you by the beginning of the 2011–2012 academic year.

Also on our Web site in May will be free science-related activities for parents and kids, called Bring Science Home.

Next issue, I will tell you about another new program—this one for enthusiasts wishing to work directly with scientists on real research. *—M.D.*

Illustration by Nick Higgins

editors@sciam.com

January 2011

FLU NETWORK

The title of Helen Branswell's "Flu Factories" is the type of sensationalism that has to be overcome for influenza surveillance to be effective and was in stark contrast to the balanced report that followed. Also, since the article was written, there has been significant progress on the implementation of a national influenza surveillance program in swine. In the program, which started in May 2009, pork producers and their veterinarians submit tissues to one of 37 veterinary diagnostic laboratories nationwide. Genetic sequences of isolated flu virus are entered into a database, then published and made available for review by experts and the public. Should there be a sequence of interest, the public or animal health surveillance systems in the state of origin can be alerted. To educate pork producers about this surveillance plan, direct mailings and other communications have been sent to more than 67,000 producers and to all state animal health officials and public health veterinarians. The results have been remarkable. During November 2010 alone, 490 samples were tested, compared with a previous monthly average of fewer than 200. U.S. pork producers and their families live with these animals, and they take the role they have in protecting public health very seriously.

Paul Sundberg
Vice President, Science and Technology
National Pork Board

"We could be sitting in the midst of a 'Galaxy-Wide Web' of alien chatter, which to us would appear like noise."

GRANT HALLMAN *HUNTSVILLE, ONTARIO*

GALAXY-WIDE WEB

Tim Folger's "Contact: The Day After" cites the well-known equation by Frank Drake, which argues for a galaxy full of sentient life. Yet no artificial signal has been detected, and we wonder why. The Drake equation includes a term *L,* which represents the life span of an alien civilization, but the implicit assumption is that such a civilization would emit signals we could both detect and recognize during its entire life span following its invention of radio. But here on Earth we can already see the failure of that assumption in two ways.

First, after less than 100 years of beaconlike transmissions, the day of the 50-kilowatt broadcast antenna is drawing to a close, as communications technology advances to coaxial, fiber-optic, and short-range, low-power systems. Even geosynchronous satellite communication is aimed down, parsimoniously covering only a portion of Earth's surface.

Second, every broadcast medium is moving to a digital format, and digital means data compression. Data compression removes redundancies—that is, any recognizable pattern in the signal—and replaces them with a compact digital code. Perfectly compressed digital data are thus indistinguishable from random noise.

These changes have overtaken human communications technology within only a few decades of Guglielmo Marconi's first work. I can only conclude that we could be sitting in the midst of a "Galaxy-Wide Web" of alien chatter, which to us, without the algorithms to decode it, appears like noise. Perhaps Drake's *L* value should be kept to under 50 years, and perhaps SETI could try to think of ways to detect digital signals embodying advanced compression—signals that look just like noise.

Grant Hallman
Huntsville, Ontario

RADIOACTIVE CIGS

The article "Radioactive Smoke," by Brianna Rego, shed more light on cigarette manufacturers and their not so ethical practices. If tobacco growers are using fertilizer on their plants, it obviously works, even though it is made from uranium-rich phosphate rock and results in polonium 210—a decay product of uranium—being inhaled with cigarette smoke. But as a nonsmoker, I wonder just where else this polonium may lie. Are food growers using the same type of fertilizer? What about cotton growers?

Rachel Allgood
Savannah, Ga.

THE EDITORS REPLY: Polonium 210 emits alpha radiation, which loses energy rapidly in the air and is blocked by clothing or by human skin. Thus, it is harmless when outside the body. The isotope does pose some cancer risk when ingested, but according to Argonne National Laboratory, the risks from inhalation—as through cigarette smoke—are about six times higher than for dietary ingestion.

SEX AND BONES

Although the discovery of internal fertilization in 375-million-year-old fossils is as important as John A. Long makes it out to be in "Dawn of the Deed," his article made the leap from placoderms to tetrapods without mention of lobe-finned fish. The fossil fish *Tiktaalik,* discovered in 2006, dates back to the same period, and its skeleton bears many more similarities to tetrapods than to the placoderms described in Long's article—including homologous arm bones and shoulder, neck and ear features. If, as his article suggests, claspers are the progenitors of tetrapod limbs, then where do nearly amphibious lobe-finned fish such as *Tiktaalik,* of the same age as his placoderms, fit in this phylogeny?

Robert Wilson
Salt Lake City

LONG REPLIES: Tiktaalik *is as close as a fish can get to being a tetrapod; the only things it lacks are fingers and toes. Unfortunately, the available fossils of tetrapod-like fish such as* Tiktaalik *and early tetrapods carry no evidence of how they reproduced. The closest living relatives of these transitional creatures are the lobe-finned*


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fishes, including the lungfishes, which spawn in water, and the coelacanth, which has internal fertilization despite lacking claspers. Internal fertilization by copulation has evolved independently many times during vertebrate evolution, with many lineages retaining simple spawning. But whether these modern-day species spawn or copulate, the equipment they use to get the job done derives from the same embryonic tissue under the direction of the same so-called hox *genes that formed claspers in placoderms.*

PRIVACY NOT PROTECTED

In "Don't Worry about Who's Watching" [TechnoFiles], David Pogue assures us that there is little to fear about the potentially vast database that an interested party might assemble about any or all of us in a matter of days. Governments are not always as benign as the ones that some of us now enjoy. History offers plenty of examples where a regime bent on total domination found it worthwhile to assemble dossiers on tens or hundreds of thousands of innocent individuals. The time, difficulty and expense required to gather information on masses of citizens have decreased exponentially, and the motivation to use such information for evil purposes can be aroused from dormancy just as easily.

David A. Burack
Brooklyn, N.Y.

EDITORS' NOTE

Many readers wrote that they were confounded by John Allen Paulos's description of the Monty Hall Problem in "Animal Instincts" [Advances]. A full description of the paradox would take up too much space here, but you can read more on this topic at www.ScientificAmerican.com/may2011/monty-hall.

ERRATUM

In "Casualties of Climate Change," Alex de Sherbinin, Koko Warner and Charles Ehrhart wrote that "the frequency of natural disasters has increased by 42 percent since the 1980s, and the percentage of those that are climate-related has risen from 50 to 82 percent." In fact, the frequency of natural disasters has more than doubled since the 1980s, but the percentage of those that are climate-related has risen only slightly, from 77 to 82 percent.

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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 ScientificAmerican.com/may2011

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Biotechnology: A brewing business in Malaysia

Malaysia is one of the 12 mega-diverse countries in the world with an estimated 15,000 flowering plant species and 185,000 animal species; accounting for 9% and 16% of the world's total, respectively.

Scientific studies suggest that 20% of the estimated 15,000 flowering plant species may possess medicinal or therapeutic properties. Biodiversity contributes to the genetic and chemical diversity that support research and development (R&D) in biotechnology.

Strategically situated in the heart of Asia's booming biotechnology market, and at the historical maritime crossroads connecting India with South Korea, Taiwan, Japan and China, Malaysia is in an ideal position to serve the global demand as a cost effective bioprocess and biomanufacturing platform in Asia.

The National Biotechnology Policy (NBP), established in 2005 took on a long term (15-year) strategy to develop and profile Malaysia as a global biotech hub. As a direct outcome of this policy the Malaysian Biotechnology Corporation was created and quickly became the lead developmental agency for biotech.

The first Phase of the NBP, from 2005 to 2010 focused on 'capacity building' and coincided with the 9th Malaysia Plan. Phase one focused on establishing the infrastructure, developing human capital and building the network of companies.

A core element in NBP is the BioNexus Bill of Guarantees. Qualified investors are assured of freedom of ownership, freedom to source funds globally, and the freedom to bring in workers with the appropriate skill sets. The bill also guarantees a strong intellectual property regime, access to shared laboratories, and BiotechCorp as a one-stop agency. BioNexus companies also receive attractive tax incentives.

The BioNexus program has attracted 188 companies. 132 are local companies, 49 have joint foreign shareholding and 9 are fully foreign owned. Investments are largely from India, Singapore, Japan, Hong Kong, Taiwan, Italy, UK and US.

According to Iskandar Mizal Mahmood, CEO of BiotechCorp, Malaysia is on track in terms of development in the industry as it contributes 2,2% to Malaysia's GDP and

has facilitated the development of 188 Bio Nexus companies.

Why Malaysia?

• In a recent report (Mar 2011) in The Times of India, Biocon Chairman, Kiran Mazumdar-Shaw commented "They are far more aggressive in attracting investments," (referring to her decision to invest in Malaysia)

"Malaysia is a compelling global destination for biotechnology, backed with world-class infrastructure and attractive tax incentives. Investing in Malaysia provides us with an international location with strategic geographical proximity to India. Biocon is pleased to be an early mover in this emerging opportunity as we dovetail our research and biomanufacturing operations with those in Malaysia to gain a global competitive advantage," said Biocon's Chairman, Ms. Kiran.

The praise for Malaysia comes from all directions and the prestigious consulting firm of Frost and Sullivan, awarded BiotechCorp with the Growth, Innovation and Leadership award as well as heaping praise on it:

"Malaysian Biotechnology Corporation has played a pivotal role in enabling the growth of the biotechnology industry in Malaysia. The BioNexus program is today recognized as amongst the best in a class of global programs."

From its agrarian past, agricultural biotechnology has been the mainstay. Leveraging on biodiversity and its strength in manufacturing, Malaysia is actively competing in industrial and healthcare biotechnology.

With the infrastructure in place, support from Government and participation of global players, biotechnology is a brewing business in Malaysia.

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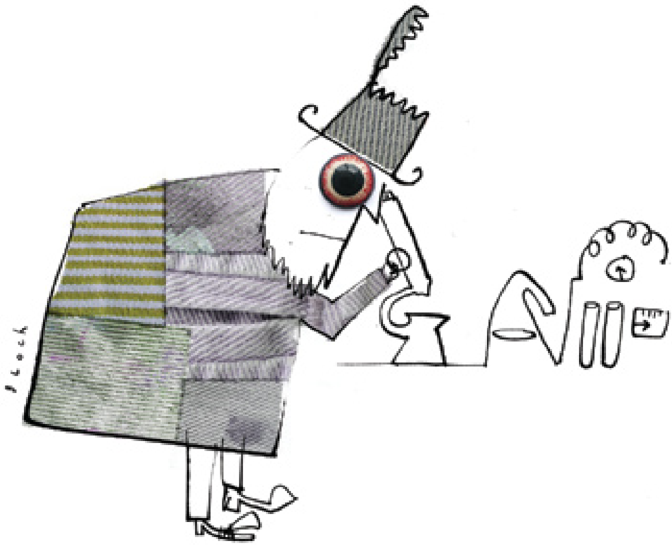
• Bio-XCell and the platform technologies acquired, spearheads commercialization efforts for Phase 2 of the NBP, from 2011 to 2015.

• Bio-XCell is a biotechnology ecosystem for industrial and healthcare biotechnology, with a focus on manufacturing and R&D. Developed by BiotechCorp and UEM Land, the park is slated to be the new regional biotech hub of Asia.

• Biocon (India), Metabolic Explorer (France) and Glycos Biotechnologies (USA) are the early global entrants to Bio-XCell. Metabolic Explorer will set up a PDO (1.3 propanediol) plant with an estimated maximum production capacity of 50,000 metric tons. Glycos Biotechnologies will focus its initial R&D on creating isoprane to support Malaysia's rubber industry.

• Strategically located in Nusajaya, Iskandar, Malaysia, the resource-rich state of Johor, Bio-XCell provides global connectivity through the network of five seaports and two international airports, all within 59 kilometers.

Opinion and analysis from *Scientific American*'s Board of Editors



Dr. No Money

Scientists spend too much time raising cash instead of doing experiments

Ever since Johannes Kepler traipsed over half of Europe wooing aristocratic patrons, scientists have grumbled about money. But their complaints these days go beyond the familiar griping about being underpaid and underappreciated. They amount to a powerful case that the system for funding science is broken—that it hinders scientific progress and fails to deliver the most bang for the buck. Fixing the system can no longer be put off.

Most scientists finance their laboratories (and often even their own salaries) by applying to government agencies and private foundations for grants. The process has become a major time sink. In 2007 a U.S. government study found that university faculty members spend about 40 percent of their research time navigating the bureaucratic labyrinth, and the situation is no better in Europe. An experimental physicist at Columbia University says he once calculated that some grants he was seeking had a net negative value: they would not even pay for the time that applicants and peer reviewers spent on them.

A vicious cycle has developed. With more and more people applying for each grant, an individual's chances of winning decrease, so scientists must submit ever more proposals to stay even. Between 1997 and 2006 the National Science Foundation found that the average applicant had to submit 30 percent more proposals to garner the same number of awards. Younger scientists are especially hard-pressed: the success rate for first-time National Science Foundation applications fell from 22 percent in 2000 to 15 percent in 2006.

Not only does the current system make inefficient use of scientists' time, it discourages precisely the kind of research that can most advance our knowledge. Many politicians go so far as to accuse scientists—particularly in politically contentious areas such as climate science—of cooking data to win government grants. They have yet to produce any evidence to support these claims, however. The real problem is more subtle. Inundated with proposals, agencies tend to favor worthy but incremental research over risky but potentially transformative work. Nobelist Mario R. Capecchi and other prominent scientists say they had trouble getting grants to make their breakthroughs. In 2009 a *New York Times* article quoted leading cancer researchers who said the war on cancer would make more progress if funders took more risks.

Funding agencies are well aware of these woes and have responded by, for example, tweaking the review process and the size of grants. That is not enough. They need to be experimenting more aggressively to find ways to fix the system. One especially promising idea is to fund people rather than projects.

That is the approach taken by the Howard Hughes Medical Institute, the largest private supporter of medical research in the U.S. It has selected some 330 researchers with a demonstrated track record of success, as well as 50 up-and-coming young scientists, and annually distributes about $500 million among them with a minimum of red tape. In 2009 three economists compared this system with the standard National Institutes of Health grant. The NIH grants last three years, end abruptly if they are not renewed and have very strict requirements—for instance, preventing scientists from shifting money from a project that is not working out to a more promising approach. Howard Hughes grants last for five years, are usually renewed, provide a grace period even if not continued and encourage reallocation of resources on the fly. The economists found that Howard Hughes grants led to higher-impact research, even when the researchers were compared with an equally elite sample of NIH applicants.

Another major private research foundation, the Wellcome Trust in the U.K., is now shifting to a similar system. The NIH started a Howard Hughes–like Pioneer Award program in 2004, but it is still tiny—only about a dozen scientists per year. Funding agencies should expand such programs considerably.

In certain cases, they might as well just give money to all qualified comers. As crazy as that sounds, the screening process does not always justify its cost. In 2009 two Canadian academics calculated that the country's Natural Sciences and Engineering Research Council spent more than C$40 million administering its basic "discovery" grants. It would have been cheaper simply to award each applicant the average grant of C$30,000. Yet another idea is a lottery system, as the Foundational Questions Institute uses for its smaller grants. Many grants are so competitive that the choice is largely a lottery anyway.

Funders and universities also need to confront tough questions such as whether graduate programs are issuing too many Ph.D.s. If a professor has more than a few doctoral students over the course of his or her career, the number of researchers competing for grants will increase exponentially.

One thing is clear: the status quo is unsustainable. Budgets are tight, and the scientific questions the world faces are pressing. We cannot afford to be squandering money and minds. SA

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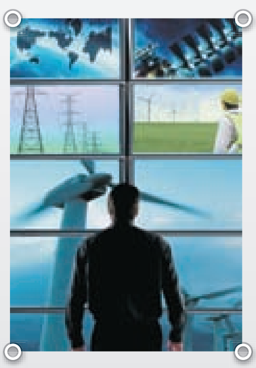
Illustration by Serge Bloch



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Daniel T. Willingham is professor of psychology at the University of Virginia and is author of *Why Don't Students Like School?* (Jossey-Bass, 2009).

Trust Me, I'm a Scientist

Why so many people choose not to believe what scientists say

A friend of mine has long held that a vaccination his son received as an infant triggered his child's autism. He clings to this belief despite a string of scientific studies that show no link between autism and vaccines. When the original paper on such a link was recently discredited as a fraud, my friend's reaction was that it will now be more difficult to persuade people of the dangers of vaccination. He is not alone: nearly half of all Americans believe in the vaccine-autism link or are unsure about it.

The paradox goes deeper. My friend insists that he trusts scientists—and again, in this respect, he is like most Americans. In a 2008 survey by the National Science Foundation, more respondents expressed "a great deal" of confidence in science leaders than in leaders of any other institution except the military. On public policy issues, Americans believe that science leaders are more knowledgeable and impartial than leaders in other sectors of society, such as business or government. Why do people say that they trust scientists in general but part company with them on specific issues?

Many individuals blame the poor quality of science education in the U.S. If kids got more science in school, the thinking goes, they would learn to appreciate scientific opinion on vaccines, climate, evolution and other policy issues. But this is a misconception. Those who know more science have only a slightly greater propensity to trust scientists. The science behind many policy issues is highly specialized, and evaluating it requires deep knowledge—deeper than students are going to get in elementary and high school science classes. A more direct approach would be to educate people about why they are prone to accept inaccurate beliefs in the first place.

Humans do seem to prize accuracy above all. We want our beliefs to be accurate—to align with what is really true about the world—and we know that science is a reliable guide to accuracy. But this desire to be accurate conflicts with other motives, some of them unconscious. People hold beliefs to protect important values, for example. Individuals who think of nature as sacred may perceive genetic modification as morally wrong, regardless of its safety or utility. People also hold beliefs that are rooted in their emotions. A flu pandemic that can cause widespread death among the innocent may cause feelings of fear and helplessness. One way to cope with those emotions is to belittle warnings of a pandemic as improbable.

In reconciling our rational and irrational motives for belief, we have become good at kidding ourselves. Because we want to see ourselves as rational beings, we find reasons to maintain that our beliefs *are* accurate. One or two contrarians are sufficient to convince us that the science is "controversial" or "unsettled." If people knew that other motives might compromise the accuracy of their beliefs, most would probably try to be on their guard.

Asking science teachers to impart enough content to understand all the issues may be unrealistic, but they might be able to improve people's appreciation for the accuracy of scientific knowledge. Through the study of the history of science, students might gain an understanding both of their own motivations for belief and of science as a method of knowing. If a student understands how a medieval worldview could have made a geocentric theory of the solar system seem correct, it is a short step to seeing similar influences in oneself.

Science history can also help students understand why scientific knowledge grows ever more accurate. It is easy for a nonscientist to dismiss an unpleasant conclusion as controversial on the grounds that scientists constantly change their minds: "First they say chocolate is bad for us, then it's good … they can't decide anything." By studying how new observations led to the revision of important theories, however, students see that science is not about immutable laws but provisional explanations that get revised when a better one comes along. They also see that scientists' readiness to change their beliefs to align with data is a source of great strength, not weakness, and why near consensus on issues such as global warming or vaccine safety is so impressive. Science may not be the only way of organizing and understanding our experience, but for accuracy it fares better than religion, politics and art. That's the lesson. SA

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Illustration by Jeffrey Decoster

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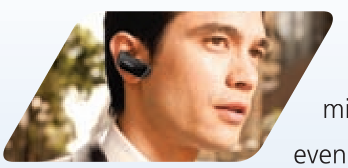

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ENVIRONMENT

Warning: Flooding Ahead

Human-induced climate change is bringing on more extreme weather

High waters: Nashville, Tenn., on May 3, 2010.

In the past year floods have submerged cities as far apart as Nashville, Tenn., and Nowshera, Pakistan. An epic heat wave touched off peat fires in Moscow that wreathed the capital in smoke. A drought in northeastern China ruined the wheat crop. Blizzards left the U.S. buried in snow—and collapsed the roof of a football stadium. "It is a reasonable question: Is human influence on climate anything to do with this nasty bit of weather we're having?" physicist Myles Allen of the University of Oxford said in a recent press briefing.

It hasn't been an easy question to answer. But now, after years of research, scientists have begun to detect a human fingerprint in many extreme weather patterns. In a study written up in February in *Nature* (a sister publication of *Scientific American*), researchers examined daily records of rainfall, snowfall and sleet from more than 6,000 weather stations between 1951 and 1999. They found a rise in cases of extreme precipitation, such as rainstorms that deliver 100 millimeters of rainfall or more in 24 hours. The uptick could not be explained by natural climate fluctuations; instead it more closely matched what the patterns that computer models of climate predict for increasing concentrations of greenhouse gases. Humanity, in other words, has likely loaded the weather dice in favor of severe storms.

The study suggests that record-breaking downpours, blizzards and sleet storms will continue—though by how much and how soon remain a mystery. The U.K.'s Met Office, the U.S. National Center for Atmospheric Research and other partners aim to bridge that knowledge gap by making regular assessments—much like present evaluations of global average temperatures—of how much a given season's extreme weather is from human influence.

Linking a particular weather event to human-induced climate change remains problematic. "We shouldn't expect that human influence should be a factor in all of these events," says climatologist Francis Zwiers of the University of Victoria in British Columbia, who led the research published in *Nature*. Still, we don't get off scot-free. *—David Biello*

MARK HUMPHREY *AP Photo*

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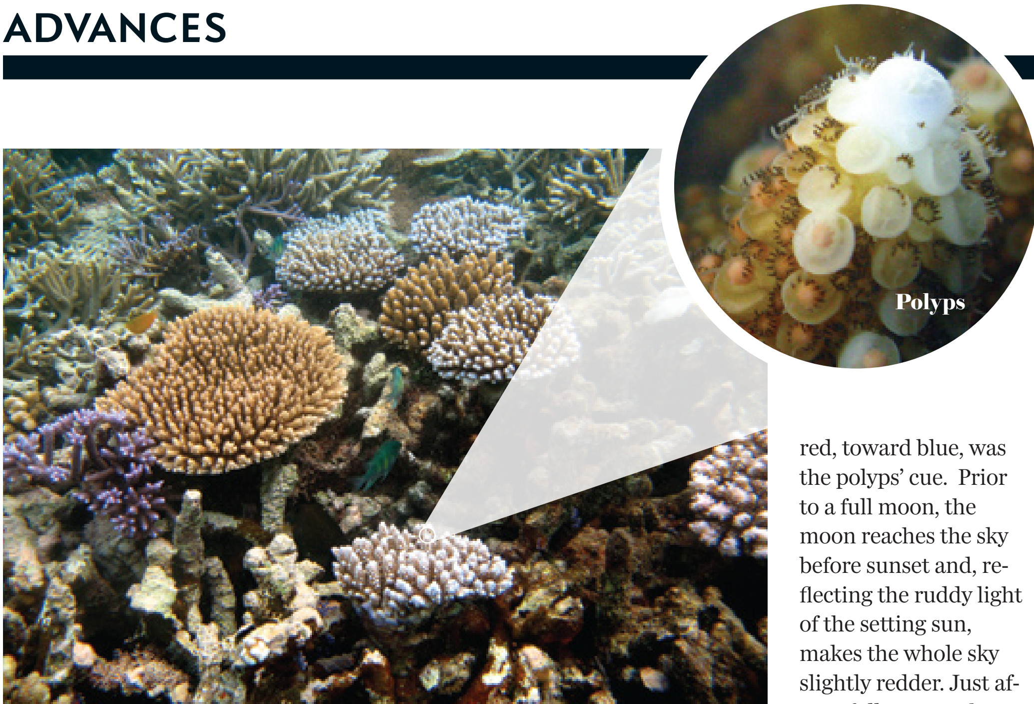


ECOLOGY

Coral in Love

Why they spawn only at twilight

It is hard to court the opposite sex when you are cemented in place, which explains why polyps—the tiny creatures whose exoskeletons form corals—do not reproduce by mating. Instead they cast millions of sperm and eggs into the sea, where they drift up to the ocean surface, collide, form larvae and float away to form new coral reefs.

Polyps may not be picky about their "mates," but they are sticklers for timing. The polyps in a coral reef will "blow" their eggs and sperm simultaneously in quick frenzies for just one, or maybe a few, consecutive nights a year—and they usually do so shortly after sunset on evenings closely following a full moon. Scientists are now beginning to solve the mystery of this feat of simultaneity.

Because polyps have no central nervous system, scientists have been at a loss as to how the individual polyps coordinate so well with one another. A reef generally picks one day during a full moon in summer to blow, for 20 minutes or so, during the twilight hours. Although scientists have yet to agree on how corals know which month to spawn, Alison Sweeney, an evolutionary biologist at the University of California, Santa Barbara, choose a narrower question: How do corals select the precise moment to blow?

Sweeney suspected that a hue shift in the twilight sky away from red, toward blue, was the polyps' cue. Prior to a full moon, the moon reaches the sky before sunset and, reflecting the ruddy light of the setting sun, makes the whole sky slightly redder. Just after a full moon, when sunset precedes moonrise, the moon is no longer there to reflect the pinkish tint, so twilight turns bluer.

To test her hypothesis, Sweeney led a team from U.C.S.B. and Duke University to the Virgin Islands in August 2009. They observed a reef of elkhorn, a common Caribbean coral, for six evenings near the time when they thought it would release eggs and sperm. Nearby they suspended an optical cable to reef depth—about 2.5 meters below the water—from a floating spectrometer. They noted shifts in the ocean's color each twilight. Consistently, it reflected the sky's color. The coral spawned during twilights of radiant blue: the third and fourth nights after a full moon, between 9:20 P.M. and about 9:50 P.M.

Sweeney, whose team reported its results in the February *Journal of Experimental Biology,* believes that like sea urchins (which also link reproduction to lunar cycles), elkhorn "see" color shifts through their skin, which contains photoreceptors of the kind found in human retinas. She is not yet sure why they prefer blue hues to red. But when the receptors recognize the right color, a biochemical reaction probably ripples through the entire reef—*now!*

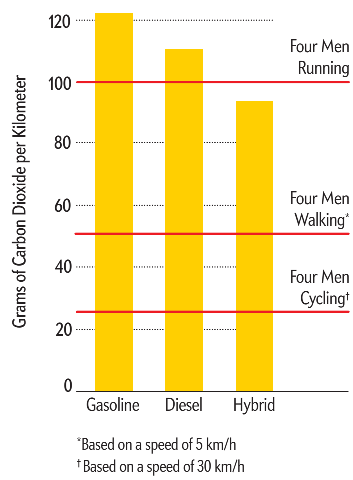
—Rebecca Coffey

COURTESY OF CHARLIE BOCH *University of California, Santa Barbara (coral)*

TRANSPORTATION

When Cars Are Greener Than People

Hybrid cars have become so eco-friendly they now trump at least one form of human locomotion. Alberto E. Minetti, professor of physiology at the University of Milan, along with his master's student Gaspare Pavei, compared the CO_2 emissions of four men walking, running and biking with the emissions of a hybrid vehicle carrying those same four men. The scientists found that four men would release more CO_2 by jogging than if they boarded a hybrid car. (On average, four women jogging would release less CO_2 than if they rode in a car because of their lower body mass.) The lesson: next time you and three male friends are late for the movies, don't run. Hail a hybrid taxi. ***—Anna Kuchment***



Graphic by Jen Christiansen

MEDICINE

Cancer Testing? There's an App for That

Physicians are using smartphones to diagnose diseases, check blood cell counts and identify pathogens in drinking water

Many people already use their smartphones as far more than mere telephones—as gadgets for Web surfing, e-mailing or listening to music. Some scientists are now turning them into handheld tools to diagnose cancer or infectious disease, track treatment progress or check water safety. Given that the handsets are so common, they could bring cutting-edge health care technology to the developing world.

Diagnosing cancer is a challenge because it requires expensive, time-consuming assays. But in a recent study published in *Science Translational Medicine,* Ralph Weissleder and his colleagues at Harvard Medical School used a cell phone and a lunch box–size machine to diagnose cancer from tiny pieces of tissue, taken via needle from the abdomens of patients with suspected metastatic cancers. Researchers mixed the samples with antibodies that bound to four known cancer-related proteins. The machine analyzed the samples using nuclear magnetic resonance—measuring levels of the antibody-bound proteins based on their magnetic properties. It then sent the results to the smartphone, which, using an app that the researchers designed, displayed the data. Because doctors don't need a laptop or desktop, it would be easier for them to assess patients outside the clinic. In comparison, results from more traditional diagnostic methods are typically not available for three days and require more invasive tissue sampling.

By using different antibodies, doctors could use the device to diagnose any form of cancer, says Harvard systems biologist and co-author Hakho Lee. They could also track treatment progress. "If there is a decrease in either the number of cancer cells or the expression levels of certain disease markers, then that means the treatment might be working," he says. He expects a product within five years.

Other researchers are taking advantage of smartphone cameras to create diagnostic microscopes. Electrical engineer Aydogan Ozcan and his colleagues at the University of California, Los Angeles, have developed a 4.5-centimeter-long phone attachment that shines LED light on biological samples, producing holograms of each cell based on how the light scatters. The phone's camera then snaps a photograph, compresses the image and sends it to a clinic for evaluation. With the ability to decipher details as small as 1/1,000th of a meter, the microscope could identify sickle-cell disease or malaria from blood samples and perform blood cell counts. The devices could bring an elegant simplicity to nations that struggle with infectious diseases.

—*Melinda Wenner Moyer*

WHAT IS IT?

A new spin on silk: Silkworms in Singapore are weaving cocoons in brilliant colors. A team at the country's Institute of Materials Research and Engineering, part of the government's lead agency for science and technology, is hoping to do away with the laborious and water-intensive silk-dyeing process by feeding domesticated silkworms (*Bombyx mori*) fluorescent molecules mixed into their natural diet of mulberry powder. The worms' silk glands take up the dye and incorporate it into the silk fibers they produce, lead author Natalia C. Tansil says. The luminescent silk, described in a recent online edition of *Advanced Materials,* also has potential applications for tissue engineering because it allows a clear—and bright—way to monitor scaffolds implanted to rebuild tissue or bone. More research is needed for this biomedical application, but Tansil is hopeful that a textile product will be available within a few years.

—*Ann Chin*

COURTESY OF A*STAR INSTITUTE OF MATERIALS RESEARCH AND ENGINEERING, SINGAPORE (*cocoons*)

Illustrations by Thomas Fuchs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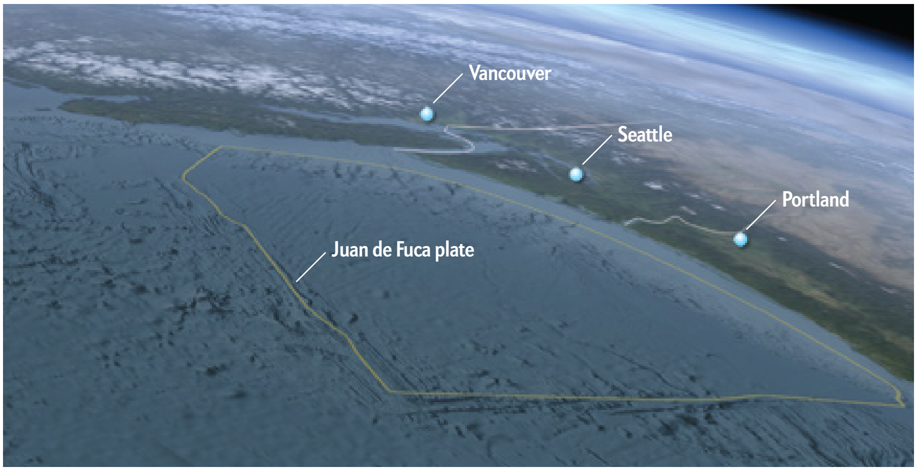
GEOLOGY

Bracing for the Big One

A series of major earthquakes have struck below the Pacific Ocean in less than a year and a half. Could the West Coast be next?



Several devastating earthquakes have rumbled beneath the Pacific in the past 15 months. In February 2010 a magnitude 8.8 temblor slammed central Chile; last September a 7.0 quake walloped Christchurch, New Zealand, leading to a 6.3 aftershock in February. The magnitude 9.0 mega quake that flattened Japan in March is tied for fourth largest in the past 110 years.

These events have led many people to wonder if they are somehow linked. Most likely, scientists say, their near coincidence is merely a statistical fluke. That doesn't mean, however, that it is necessarily safe to come out from under the bed. The best gauge of quake risk is the geologic record. And new data on that record tell a disturbing story, especially in the northeastern Pacific.

Although most people may consider southern California to be the most earthquake-prone region in the nation, the Cascadia subduction zone is arguably the biggest seismic hazard in the U.S. It parallels the coast and poses a seismic threat to cities such as Vancouver, B.C., Seattle, and Portland, Ore. At that subduction zone, the tiny Juan de Fuca plate slides eastward underneath North America between 30 and 40 millimeters a year—but this interface has apparently been locked for centuries. "This subduction zone stands out as the big elephant in the corner," says Chris Goldfinger, a marine geologist at Oregon State University. "It sits quiet for hundreds of years and then goes off all at once."

New data suggest that the northern portion of the subduction zone, from the middle of Vancouver Island to the Washington-Oregon border, has a 10 to 15 percent chance of suffering a magnitude 8.0 or greater quake in the next 50 years. The southern portion, stretching from the Washington-Oregon border to California's Cape Mendocino, has a 37 percent chance of the same-size quake over that same interval. Goldfinger and his colleagues expect to publish the data in an upcoming USGS report. The next big one, he says, "is going to happen. It's just a matter of narrowing down the timeline."

—Sid Perkins

EXPLAINER

How do scientists measure the speed of tectonic plates?

The best way to measure how quickly two tectonic plates converge is to use the Global Positioning System. By repeatedly checking the distances between specific points on two different plates, researchers can assess long-term rates of convergence and measure sudden movements, such as Japan's 2.4-meter (eight-foot) leap eastward during the March 11 quake. Before the advent of GPS, scientists relied on rocks in the ocean floor, which, when they cool, record the direction of the earth's magnetic field. Knowing when and how often the field has flipped in the past enables researchers to calculate the rate at which new ocean crust forms at mid-ocean ridges. Another technique is to sample and map rock formations on both sides of a tectonic interface—especially formations that have a distinctive composition or an unusual assemblage of fossils. *—S.P.*

ENERGY

The Newest Nuclear Plants

As always, safety is a balancing act

The first new nuclear reactor in the U.S. in nearly three decades is taking shape outside Augusta, Ga. Southern Company has dug up a patch of red clay down to bedrock for the foundation of a new AP-1000—a new generation of reactor with passive safety features that keep working even when the power goes out. Southern plans to build two such AP-1000s in the next six years, and other utilities have plans for 12 more, along with another six new reactors of various designs, all of them with passive safety features.

Safety features that operate in the absence of electricity or human intervention were lacking at the Fukushima Daiichi nuclear power plant in Japan, which was built in the 1970s. The March earthquake knocked out the plant's connection to the grid, and the subsequent tsunami damaged backup generators and electrical equipment, crippling cooling systems and allowing reactor cores to heat up. Each AP-1000, in contrast, has a giant tank of water that sits above the reactor core. In the event of a potential meltdown, the heat buildup would trigger a valve, allowing the water to flow into the reactor.

The AP-1000 also has an open-sky design that, in a pinch, uses air currents to cool the reactor. In a departure from standard designs, the outer concrete building that encloses the reactor's primary concrete and steel shell has vents near the roof. In a meltdown, natural convection would pull in air.

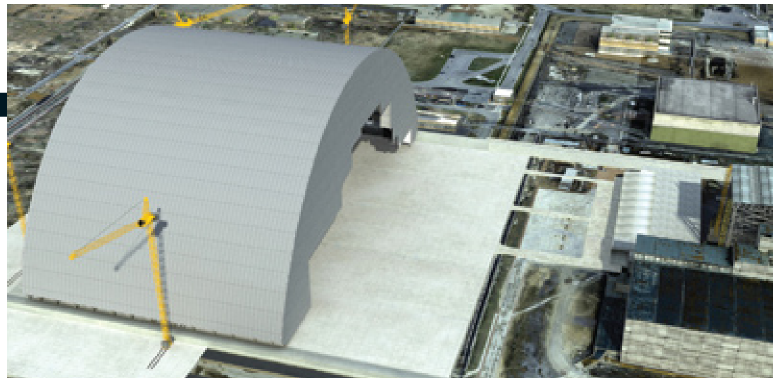
Convection would also spread radioactive particles out through the roofline vents, critics point out. Engineers counter that eliminating all risk is impossible; the best they can do is strike an acceptable balance between safety and cost. "With earthquakes, there are limits to what you can do," says Michael Golay, a nuclear engineer at M.I.T. "What risk are you willing to tolerate?" *—David Biello*

Illustration by Don Foley

ENVIRONMENTAL ENGINEERING

Steel Rainbow

Twenty-five years after Chernobyl, the world's largest movable structure is set to seal off the failed reactor for good



COURTESY OF NOVARKA

Imagine a metal arch that, at its highest point, is taller than the Statue of Liberty. Now picture it sliding along the ground for a distance of about three football fields, making it the biggest movable structure ever built. Under this steel rainbow, engineers are planning to entomb the site of the worst nuclear accident in history, at the Chernobyl power plant in the Ukraine, using robotics to dismantle the ruins and permanently seal the wreckage.

After reactor number 4 exploded at the plant on April 26, 1986, sending radioactive dust as far as Japan and the U.S., the Soviet Union put up a structure of steel and concrete, commonly known as the sarcophagus, over the reactor to contain the radioactivity. "It was really quite a remarkable feat, but after 25 years, it's in danger of collapse," explains civil and environmental engineer Eric Schmieman of the Battelle Memorial Institute. The structure, which was put up as quickly as possible to limit worker exposure to radiation, was never meant to last forever.

It was designed "like a house of cards," Schmieman says, with pieces of metal leaning against one another and hooked together. "There are no welded joints or bolted joints—it wouldn't take much of a seismic event to knock it down."

French construction company Novarka is working on a replacement, the New Safe Confinement (NSC), which Schmieman helped to design. Because the reactor is still radioactive, architects designed the NSC with worker safety in mind. The arch will not be built over the sarcophagus but will be assembled nearby from prefabricated segments. Workers will use hydraulic jacks to slide the arch about 300 meters along Teflon bearings until it covers the sarcophagus. Once engineers seal the reactor, they will remotely maneuver three robotic cranes inside the NSC to dismantle the sarcophagus and reactor and to clean up any leftover radioactive dust.

Novarka aims to finish fabricating the NSC by the summer of 2014, at a cost of $2.1 billion from 29 countries. It is expected to last at least 100 years.

—Charles Q. Choi

PHILIP LAURELL *Gallery Stock*

MEDICINE

Beating Back the Bugs

Some hospitals have turned a corner in fighting deadly infections

It is the ultimate paradox of American health care: going to the hospital can kill you. Every year nearly two million hospital-acquired infections claim roughly 100,000 lives and add $45 billion in costs; that is as many lives and dollars as taken by AIDS, breast cancer and auto accidents combined. And with antibiotic resistance rising steadily, those numbers promise to climb even higher.

Even more staggering than the numbers is that most of these infections are preventable. The Institute of Medicine has long since determined that if hospital staff would make some minor adjustments to their routines—like washing their hands more—the problem could be significantly minimized.

Washington is now starting to crack down. On January 1 the Centers for Medicare & Medicaid Services (CMS) began requiring that all acute care facilities report the number of intensive care unit patients who develop bloodstream infections. Eventually the information will be made public, requirements will expand to include all types of hospital-acquired infections, and the level of Medicare reimbursement will be tied to how effective hospitals are at reducing infection rates.

Some medical centers have already taken the initiative and started making changes. A handful "have virtually eliminated some forms of infection that other hospitals still think are inevitable," said Donald M. Berwick, who heads the CMS, in congressional testimony last year.

One of them is Claxton-Hepburn Medical Center, a rural hospital with a 10-bed intensive care unit in Ogdensburg, N.Y. It has nearly wiped out ventilator-associated pneumonia (VAP)—a hospital-acquired infection that occurs in 25 percent of all people who require mechanical ventilation—just by making a handful of changes to its protocol. Instead of laying patients flat, nurses keep them elevated at a 30-degree angle, which studies show is better for the lungs and does not, as previously thought, increase the risk of bedsores. Rather than leaving patients sedated, doctors now wean them from sedatives once a day to test their progress—another trick proved to reduce the length of stay. Nurses also take care to brush patients' teeth every day and to clean their mouths and gums every few hours because oral infections often spread to the lungs. In the five years that followed the adoption of these practices, not a single case of VAP emerged.

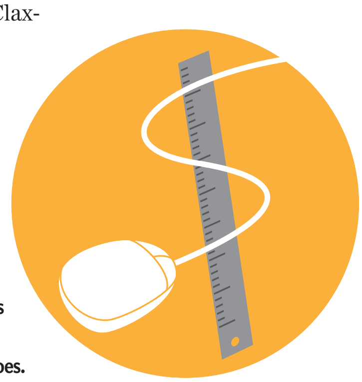
Claxton-Hepburn is not the only hospital with success stories to share. In fact, dozens of New York–based hospitals—including ones much larger than Claxton-Hepburn—managed to cut their VAP rates in half by employing similar methods. And in Michigan 103 intensive care units eliminated catheter-related bloodstream infections during an 18-month study; hospital workers credited evidence-based practices and simple checklists. With solutions that cost less than the penalties, more hospitals are sure to follow Claxton-Hepburn's lead.

—Jeneen Interlandi

ECONOMICS

The Prices Are Right

Economists find a faster, cheaper way to measure inflation



Even in the information age, the U.S. Bureau of Labor Statistics still gathers much of its data the old-fashioned way. Workers make phone calls to find out what dentists charge for pulling teeth, and they visit stores to write down the prices of CDs and Russet potatoes. In the end, the data are accurate but take a month or so to compile and analyze.

To speed things up, Alberto Cavallo and Rigoberto Rigobon, economists at the Massachusetts Institute of Technology, created the Billion Prices Project (bpp.mit.edu). Software indexes Web sites to track prices of more than five million goods from 70-plus countries and spits out inflation rates in real time.

Although the Billion Prices Project is not intended to replace official statistics—it leaves out many service prices, like haircuts and dental visits, that aren't readily accessible on the Internet—the quick data can come in handy during times of economic uncertainty. After the February 2010 Chilean earthquake, the government used Cavallo and Rigobon's figures to monitor food prices and watch for any steep rises. Cavallo is now working on a way to apply the method to calculations of gross domestic product, the total value of all goods and services produced by a country. "GDP is what determines if a recession is imminent," says economist Laurence Ball of Johns Hopkins University.

—Michael Easter

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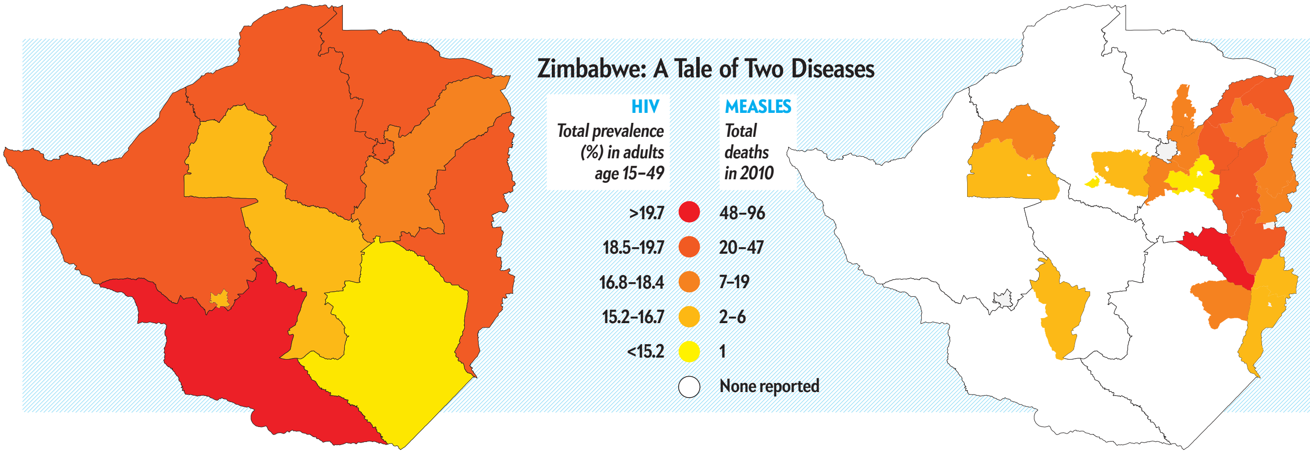


SOURCES: U.N. OFFICE FOR THE COORDINATION OF HUMANITARIAN AFFAIRS; JOINT U.N. PROGRAM ON HIV/AIDS; WHO

INFECTIOUS DISEASES

HIV vs. Measles

Pediatric HIV may be hindering measles eradication efforts

Measles has been all but eradicated in the developed world, but it still claims more than 160,000 lives in developing countries. Sub-Saharan Africa, in particular, has been hit hard in the past few years. A 2009 outbreak in Zimbabwe, for instance, afflicted 8,000 people and killed 517. Some public health workers blame lax vaccination efforts, but the real culprit may be HIV.

Studies show that infants with HIV do not respond well to the measles vaccine even when given a second dose at nine months, as the World Health Organization (WHO) currently recommends. A 2008 study in Malawi found that the extra dose only boosted measles immunity to 64 percent. Worse yet, a 2009 study in Kenya found that only 33 percent of HIV-infected children who had been vaccinated for measles at birth still had antibodies to the virus at age five. "Normally measles immunity will last 10 years and often for life," says William Moss, a public health researcher at Johns Hopkins University who studies HIV and measles in Zambia.

The implications for immunization efforts are serious. The current vaccination schedule is inadequate for countries with high HIV levels, says Anna Nilsson, an immunologist at the Karolinska Institute in Sweden and co-author of a March paper on measles and HIV in *PLoS Pathogens*. "The traditional approach has been to give the same vaccine at the same age to all children," she says. "But here we have a group of very vulnerable children who need special consideration." More than two million children in sub-Saharan Africa carry HIV.

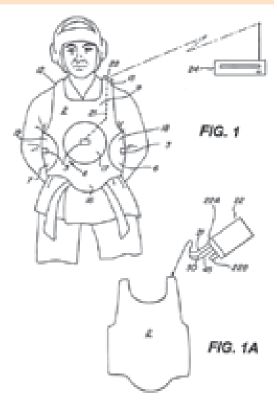
Fortunately, HIV-infected children can develop immunity to measles if they receive antiretroviral therapy before vaccination. When the HIV-infected five-year-olds in the Kenya study were revaccinated after six months of antiretroviral treatment, their measles immunity rose to 78 percent. And Nilsson and her colleague found that treating HIV-infected infants with antiretrovirals preserves a type of immune cell that improves vaccine response. "For immunization efforts to be successful in HIV-infected children, you also have to provide antiretrovirals," Nilsson says. The WHO is working to make retrovirals more available. Now they have an added incentive. *—Erica Westly*

PATENT WATCH

Registering impacts in sports: Masters of the martial art of Tae Kwon Do have gotten so lightning-quick that even a team of four judges placed around a competition ring can have a hard time keeping up. That is where a human-computer interface invented by Jin Y. Song, a veteran Silicon Valley–based electrical engineer and Tae Kwon Do black belt, comes in. The invention relies on three different types of sensors embedded in traditional Tae Kwon Do head and torso protectors, plus modern wireless technology and magnets to accurately track and score blows to the body and head delivered in the blink of an eye. "If someone pushes you really hard, this thing will not pick it up," says Song, referring to the pressure sensor located near the torso. "There has to be a quick impact."

Impacts to the head are picked up by the same acceleration detectors found in car air bags. Magnets embedded in foot protectors alert a third class of sensors that impact from a foot is imminent, which helps the sensors distinguish valid hits from incidental contact with other parts of the body. (A BlackBerry uses the same magnet to turn off when slid into a case.) Finally, wireless transmitters convey signals to a computer sitting on top of a nearby scorer's table, where officials keep track of who is winning the match.

Song received final approval for his patent in February. The device has already been used successfully to score a handful of martial arts competitions, including the World University Taekwondo Championship in Spain and a major martial arts competition in Beijing. The International Olympics Committee is also currently considering using the device to score the 2012 Games. Song is now in the process of adapting the technology for use in other sports, among them football, which is beset by a high occurrence of concussions. He thinks the sensor could be valuable for monitoring blows to the head of football players. *—Adam Piore*



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DO THE MATH/METHODS

Why Bayes Rules

A new book about the now ubiquitous theorem traces its road from 18th-century theology to 21st-century robotic cars

Google has a small fleet of robotic cars that since autumn have driven themselves for thousands of miles on the streets of northern California without once striking a pedestrian, running a stoplight or having to ask directions. The cars' ability to analyze enormous quantities of data—from cameras, radar sensors, laser-range finders—lies in the 18th-century math theorem known as Bayes' rule. The formula has survived decades of controversy and marginalization to emerge as the cornerstone of some of the most sophisticated robotics projects now under way around the world.

Discovered by English clergyman Thomas Bayes, the formula is a simple one-liner: Initial Beliefs + Recent Objective Data = A New and Improved Belief. A modern form comes from French mathematician Pierre-Simon Laplace, who, by recalculating the equation each time he got new data, could distinguish highly probable hypotheses from less valid ones. One of his applications involved explaining why slightly more boys than girls were born in Paris in the late 1700s. After collecting demographic data from around the world for 30 years, he concluded that the boy-girl ratio is universal to humankind and determined by biology.

Many theoretical statisticians over the years have assailed Bayesian methods as subjective. Yet decision makers insist that they bring clarity when information is scarce and outcomes uncertain. During the 1970s John Nicholson, the U.S. submarine fleet commander in the Mediterranean, used Bayesian computer analysis to figure out the most probable paths of Soviet nuclear subs. Today Bayesian math helps sort spam from e-mail, assess medical and homeland security risks and decode DNA, among other things.

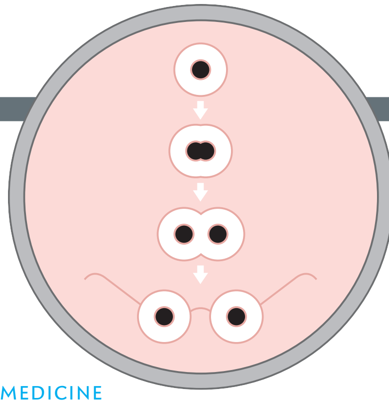
Now Bayes is revolutionizing robotics, says Sebastian Thrun, director of Stanford University's Artificial Intelligence Laboratory and Google's driverless car project. By expressing all information in terms of probability distributions, Bayes can produce reliable estimates from scant and uncertain evidence.

Google's driverless cars update information gleaned from maps with new road and traffic data from sensors mounted atop the vehicles. Google hopes that robotic cars will one day halve the number of road fatalities, cut energy consumption, fit more densely onto crowded roads and free commuters for more productive activities—like dreaming up even better ways to use a 250-year-old theorem.

—*Sharon Bertsch McGrayne*

McGrayne is author of *The Theory That Would Not Die, How Bayes' Rule Cracked the Enigma Code, Hunted Down Russian Submarines & Emerged Triumphant from Two Centuries of Controversy* (Yale University Press, 2011).

Google's driverless cars use Bayesian methods.



MEDICINE

A Cure within Sight?

Embryonic stem cells may help treat a leading cause of blindness

Until now, patients who suffer from one of the most common causes of vision loss have had little hope for treatment. Age-related macular degeneration, or AMD, typically strikes people older than 60 by thinning a layer of cells at the back of the eye known as the retinal pigment epithelium. This layer of cells eliminates waste from the eye and nourishes photoreceptors, the neurons that absorb and convert the light that creates the images we see. As the disease progresses, photoreceptors die, and patients lose central vision—the ability to see what is directly in front of them; peripheral vision is not affected.

Embryonic stem cells may be able to halt the progress of the disease. When researchers used stem cells to create new retinal pigment cells and injected them under the retinas of rats, the new cells helped restore the epithelium, temporarily stopping the degeneration of the retina and rescuing threatened photoreceptors.

This spring scientists will test this method in patients for the first time. The clinical trial, led by biotech company Advanced Cell Technology and conducted at U.C.L.A.'s Jules Stein Eye Institute, will focus on treating the most common form of macular degeneration, known as atrophic (dry) AMD. "There's a desperate need to be thinking about cell therapies for blinding diseases because not a lot else is coming down the pike," says Marie Csete, former chief scientific officer at the California Institute for Regenerative Medicine, a research funding agency (she is not involved in the trial).

Some critics warn that patients' immune systems could reject the foreign cells, and that undifferentiated stem cells could turn into cancer cells. Robert Lanza, chief scientific officer at Advanced Cell Technology, says his team has addressed both concerns. For one, the eye is immune-privileged, meaning it is less likely than other organs to reject foreign tissue; indeed, rejection was not an issue in trials on rats. The company has also developed a test to detect a single undifferentiated stem cell among the retinal pigment cells they will give to patients.

If trials prove the treatment is safe, Lanza will test it on patients with earlier stages of AMD, the better to prevent the onset of the disease. At best, though, the treatment would spare vision but not restore sight that has already been lost. —***Sonya Collins***

COURTESY OF GOOGLE (*car*)

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SCIENTIST IN THE FIELD

"Let's Go for It"

The leader of the government's push into alternative energy talks about fuel-making microbes, the next industrial revolution and how soon his high-risk projects will reach the market

COURTESY OF KEN SHIPP *U.S. Department of Energy*

PROFILE

NAME
Arun Majumdar

TITLE
Director, Advanced Research Projects Agency–Energy

LOCATION
Washington, D.C.

What is ARPA–e's mandate?
The wise thought leaders who created ARPA-e felt that a place to go and try out a new, high-risk idea did not exist. [That is] what ARPA-e was created for.

We are saying that if energy is the next industrial revolution and if we are going to be competitive in this globally competitive world, and we are falling behind right now, gosh, let's go for it. You need ARPA-e to look for short-term translation of science into technology.

What kinds of projects is ARPA-e funding?
Scientists at Lawrence Berkeley National Laboratory are making progress on electrofuels [using microbes to turn carbon dioxide back into liquid fuels similar to gasoline]. They have got a new catalyst that is cheaper, and they are taking that catalyst and attaching it to a microbe, and that's supposed to produce the hydrogen that the bug will consume to produce electrofuels. I don't think they have any idea whether the catalyst will actually work when attached to the bug, but you've got to just try it out. Now that's risky. But there are slightly less risky projects as well.

This high-risk research also includes developing better batteries for electric cars, cheaper photovoltaics and power electronics (superefficient electrical converters). When will these projects start to deliver?
My most optimistic estimate is 10 years for when these products will actually be in the hands of consumers or placed in the energy infrastructure. But frankly, look at how long the Internet took, from 1968, and ARPAnet to the late 1980s. That's 20 years. That's the sort of timescale we should be looking at.

Which programs can deliver fastest?
Electrofuels are really in an early stage. I don't think we should expect that any time soon. Maybe power electronics.

How do you decide when something's a failure?
Usually if a project does not meet its milestones [after an extension of] two or three months. We give them a little window instead of just cutting them off.

Still, our primary goal is to help researchers reach their milestones and move forward. We tell our folks, look, if something's not working and we terminate a project, don't take it personally. Come back again, and we will try to support you.

—Interview by David Biello

QUOTABLE

> ***"And Houston, Discovery, for the final time, wheels stopped."***
>
> —Steven W. Lindsey of the U.S. Air Force guiding the shuttle *Discovery* back from its final flight.

COMMENT AT ScientificAmerican.com/may2011

NEWS SCAN

Genius

The FDA approved biotech drug Benlysta to treat lupus, the first new treatment for the autoimmune disease in 50 years. It is also the first drug ever developed specifically to target the debilitating affliction. Call your broker.

A study in rats showed that poor nutrition during pregnancy caused a higher risk of disease for offspring in later life. An apple a day could keep the doctor away 50 years from now.

The last flight of shuttle *Discovery* marked the beginning of the end of the 30-year-old "space bus" program. After June's final *Atlantis* mission, the U.S. will have to depend on Russia to get astronauts to the International Space Station. Holy Sputnik.

Gamblers beware: sleep deprivation may increase a sense of optimism, causing people to take bigger risks. No wonder casinos hand out free cigarettes and hide the clocks.

Self-proclaimed tiger-blooded, Adonis-DNAed warlock Charlie Sheen was labeled bipolar by "experts" who have never met him.

—George Hackett

Folly

COURTESY OF NASA (shuttle); PETER SAMUELS *Getty Images* (rat); JEAN BAPTISTE LACROIX *Getty Images* (Sheen); GETTY IMAGES (dice)

Nancy Shute covers science and medicine for NPR, *National Geographic* and *U.S. News & World Report*. She is tracking how improvements in the way clinicians and patients communicate and make decisions affect health outcomes.

Beyond Mammograms

Conventional breast cancer screening tests are far from perfect. What's next?

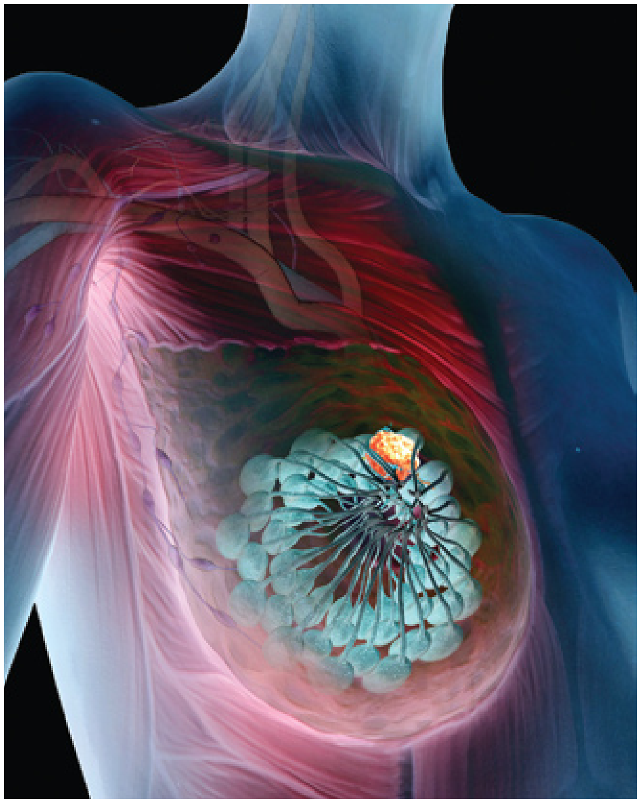
Find a breast cancer tumor when it is tiny, and a woman will probably beat the disease. Find that same malignancy when it is larger or has spread to other organs, and she is far more likely to die, even after surgery, radiation and chemotherapy. Finding breast tumors before they turn deadly is a challenge and one that medical technology has so far failed to master.

"We desperately need better breast cancer screening tools," says Otis Webb Brawley, chief medical officer at the American Cancer Society. His organization promotes mammography in an effort to reduce the 40,000 deaths from breast cancer every year in the U.S. But that emphasis, Brawley fears, leads engineers and medical device manufacturers to presume that the problem of breast cancer detection is not worth their attention, because it has been solved. It has not. Mammograms miss up to 20 percent of tumors, and an average of one out of 10 readings mistakenly identifies healthy breast tissue as possibly malignant. Those false positives mean that women who try to do the right thing by going in for routine cancer screening face a substantial risk of needless biopsies (which can themselves be disfiguring and interfere with treatment later on) and expense, as well as the misplaced fear that they have cancer when they really do not.

Mammography's shortcomings have spawned controversy and confusion. In 2009 the U.S. Preventive Services Task Force (USPSTF) determined that routine mammograms would save too few lives of women ages 40 to 49 to justify the number of false positives and unnecessary biopsies that would result in that age group. Medical societies and patient advocacy groups attacked the recommendation; the American Cancer Society still advises women in their 40s to undergo mammography every year. Some health experts fret, though, that the USPSTF finding has discouraged more than a few women, not just those in their 40s, from getting tested. "It's made women more skeptical about the test," says Sheryl Gabram-Mendola, a surgical oncologist at Emory University's Winship Cancer Institute. "Women say, 'I'm just not going to do it, I'm too busy.'"

Even before the 2009 controversy, however, women were forgoing screening mammograms. According to the most recent data from the U.S. Centers for Disease Control and Prevention, the percentage of women who have undergone mammograms within the previous two years has dropped a bit across all age groups. For women 40 to 49, the number fell from 64.3 percent in 2000 to 61.5 percent in 2008—which makes sense if mammograms are unhelpful as screening tests in that age group. For women 50 to 64, it fell from 78.7 percent in 2000 to 74.2 percent in 2008—which is worrisome given that the evidence shows mammograms are clearly beneficial for women 50 and older.

Better tools could help encourage screening and make it more useful for women of all ages. No method currently under study is robust enough yet to supplant mammography. But researchers and clinicians hope that a greater understanding of the physiology and biochemistry of breast cancer, combined with more dexterous technology, will one day result in screening tools that can replace or inexpensively supplement mammograms so that the results will be more trustworthy.



Early detection: Tests are ongoing to see if sound, light or tissue elasticity could help spot a tumor (*yellow*) early.

CORBIS

TODAY'S OPTIONS

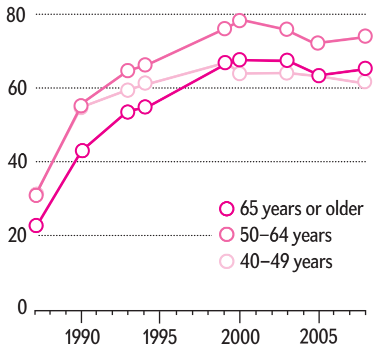
Mammography, which has been used to detect tumors since the 1970s, misses some cancers and wrongly suggests the presence of others because it is based on low-dose x-rays, which have inherent limitations in their ability to resolve tumors. When viewed with x-rays, a malignancy appears lighter in color than does normal breast tissue. X-rays also pick up white specks of calcium deposits that may be generated by a tumor as it grows. But x-rays are not good at spotting tiny tumors, partly because of a lack of contrast and partly because the calcifications associated with tumors

are much smaller than benign deposits and therefore easy to overlook. Nor are x-rays good at detecting tumors in dense breast tissue, which also reads as white; many women younger than 50 have dense breasts. Finally, mammograms cannot indicate for sure whether an unusual mass is cancerous.

Two other commonly used imaging techniques—magnetic resonance imaging (MRI) and ultrasound—often supplement mammography to detect breast cancer but are not yet reliable enough to be used by themselves for screening. MRI uses magnetism and radio waves to measure differences in the water content of tissue, which provides more detail about differences in the composition of breast tissue than do x-rays. But because a benign cyst often looks like a tumor on an MRI, screening with MRI also increases the rate of false positives. For that reason, the American Cancer Society recommends annual MRI screenings only in women with a strong family history of breast or ovarian cancer. In addition, breast MRIs are too expensive for routine use in the general population, running $2,000 to $6,000 a test compared with a few hundred dollars for a mammogram.

Ultrasound relies on high-frequency sound waves to characterize the internal structures of the breast. Unlike MRI, it can determine if a lump is a harmless, fluid-filled cyst. But its images cannot distinguish malignant tumors from benign growths filled with harmless breast tissue. It thus gives more false negatives than mammography does, which is why it is less than ideal as a stand-alone method for initial screening.

Mammography Use by Age Group (percent)



Troublesome trend: **The percentage of women having mammograms to screen for breast tumors began a general decline after the year 2000. New tools for cancer detection could help improve participation rates.**

FRESH IDEAS

Researchers, in their quest for better solutions, are experimenting with new twists on an age-old method: feeling for lumps. Tumors are stiffer than healthy breast tissue—which is why they feel different. The problem with waiting until a tumor has grown large enough to be felt, however, is that the delay increases the odds that the cancer will have spread by the time it is diagnosed. The goal is to create ways of detecting that stiffness while a tumor is still too small to be felt by human hands.

One method for measuring such stiffness depends on a combination of low-frequency sound waves and MRI. Dubbed magnetic resonance elastography, the technique was first developed more than a decade ago by Richard Ehman, a radiologist at the Mayo Clinic. Currently applied to the diagnosis of nonmalignant liver diseases, the approach is now being tested on breast tumors. Patients are scanned in an MRI while sound waves with a frequency of 60 hertz pass through plastic tubes to the breasts. The MRI picks up tiny variations in how tissue is moved by the sound waves. Ehman says his team has gotten pretty good at distinguishing between normal and malignant breast tissue based on the stiffness revealed by the MRI. But for elastography to work as a population-wide screening tool, the cost of using an MRI would have to be much lower.

Another technique for measuring tissue stiffness dispenses with the expense and claustrophobia of an MRI. Bruce Tromberg, a biomedical engineering professor at the University of California, Irvine, has built a handheld scanner that sends near-infrared light through the skin and into the breasts and then measures how the light energy scatters on its path through the body before it gets reflected back to the scanner. The light photons travel differently through tumors than through normal tissue. The experimental device is being tested in cancer patients to see whether it can be tuned to accurately measure tumor shrinkage in response to therapy. Tromberg hopes, though, that the technology can eventually be refined enough to spot malignancies while they are still microscopic.

A simpler screen, like a blood test, would be ideal. Physicians do have blood tests that detect the recurrence of breast and ovarian cancer, such as by measuring a molecule called CA125, but they are not accurate enough for large-scale screening. Several researchers, however, are tracking chemical markers in the blood and in the breath with the goal of creating screening tools that could someday not just find cancer but also indicate how dangerous it is likely to be.

Emory's Gabram-Mendola and chemists at the Georgia Institute of Technology have found markers in the breath of 20 breast cancer patients that were not present in the breath of 20 control subjects. The team is not focusing on fully replacing mammography but on saving it to use as a follow-up tool in places where resources are scarce. "There is a huge need to come up with something that can be used in countries where mammography is less available," says Charlene Bayer, who is leading the effort at Georgia Tech. A breath test performed in a doctor's office could also have great appeal for the many women in developed countries who shun screening mammograms because of the discomfort and inconvenience.

Meanwhile developing a single, perfect detection tool for spotting breast cancer remains a tall order. "The technology needs to be able to identify many, preferably most or all, of the people who have the disease," says David Dershaw, attending radiologist and emeritus director of breast imaging at Memorial Sloan-Kettering Cancer Center in New York City. "It needs to be reasonably noninvasive, tolerable and acceptable to people so they will undergo the test. It needs to be not very expensive. And it has to be widely available." Nothing under study fits that bill better than mammograms do—at least for now.

Where does that leave women in their 40s? Many doctors who no longer advise mammograms for most women younger than 50 continue to suggest them for those with a family history of breast or ovarian cancer. But for now the majority of women in their 40s will have to continue to struggle with the to-screen-or-not-to-screen question—and a realization that when it comes to tracking down breast cancer, there is still no perfect tool. SA

SOURCE: *HEALTH, UNITED STATES, 2010, WITH SPECIAL FEATURE ON DEATH AND DYING.* ANNUAL REPORT BY NATIONAL CENTER FOR HEALTH STATISTICS, 2011

Graphic by Joshua Korenblat

David Pogue is the personal-technology columnist for the *New York Times* and an Emmy Award–winning correspondent for *CBS News*.

Gadgets Are Garbage

Your brand-new device is about to be obsolete. Save it from the trash heap

Every now and then the public rises up to make an industry clean up its environmental act. As a result, car companies now offer hybrids, electrics and alternative-fuel cars. Beverage companies are making their bottles with a lot less plastic. New laws have reduced the chemicals that cause acid rain by 76 percent since 1980. And so on.

One industry in particular, however, continues to leave a disastrous eco-wake, because no such public pressure exists: consumer electronics.

You know those one billion cell phones we buy every year? Those 100 million cameras? That infinitude of laptops, Game Boys, TV sets and music players? Most of the ones we replace go to the dump. The Environmental Protection Agency calculated that in 2007, we threw away 2.25 million tons of electronics—82 percent of it into the landfill. That's a lot of toxic chemicals and nasty metals that you really, really don't want leaching into the water supply.

So where's the public outcry? Where are the public service announcements, the lobbyists, the national consciousness-raising? It doesn't exist, for one simple reason: the disposability at the heart of the industry's business model is too attractive to all concerned.

It's fairly easy to give away or sell your old car, clothing, baby gear or furniture; those things may still have value after you finish with them. But electronics? Not so much. Who would want your four-year-old cell phone, your black-and-white iPod, your two-megapixel camera?

Verizon's free-phone-upgrade program was called New Every Two. That program recently ended, but it is a good-enough description of our national obsession with owning the coolest and newest electronics. Most people would start to feel self-conscious wielding a three-year-old phone, camera, music player or laptop. They observe that the latest gadgets are sleeker, faster and cooler-looking. And presto: it's time to upgrade.

That is the industry's business model, and it works spectacularly well. Neither we nor the manufacturers have any incentive to change. They're not going to try to sell *fewer* products, and we wouldn't want them to. Will there ever be a rally where people chant, "Stop improving the gadgets" and "Slow down the pace of progress"?

No, the most realistic solution is to leave the business model alone—but to fight its wasteful consequences on two fronts. First, we can pressure the electronics companies to make the products less damaging. Factors that nobody used to care about (hormones in milk, fuel efficiency in cars) have become important marketing points. Why couldn't electronics companies tout energy efficiency, nontoxic components and minimal packaging in their advertising?

Apple does that. Its environmental report-card page (www.apple.com/environment/reports) tracks the greenhouse impact of every product not just while you own it but even during its manufacture and recycling. Apple also touts its compact packaging, recycling-valuable materials (such as aluminum) and nontoxic chemicals. There is no reason other companies' environmental practices can't be sales points, too.

Second, we consumers should recycle our gadgets when we finish with them. If the gizmos are fairly new, you can sell them—either on eBay or to "recommerce" sites such as Gazelle.com. They send you a shipping box for your old gear, pay you for it, and then resell or recycle it.

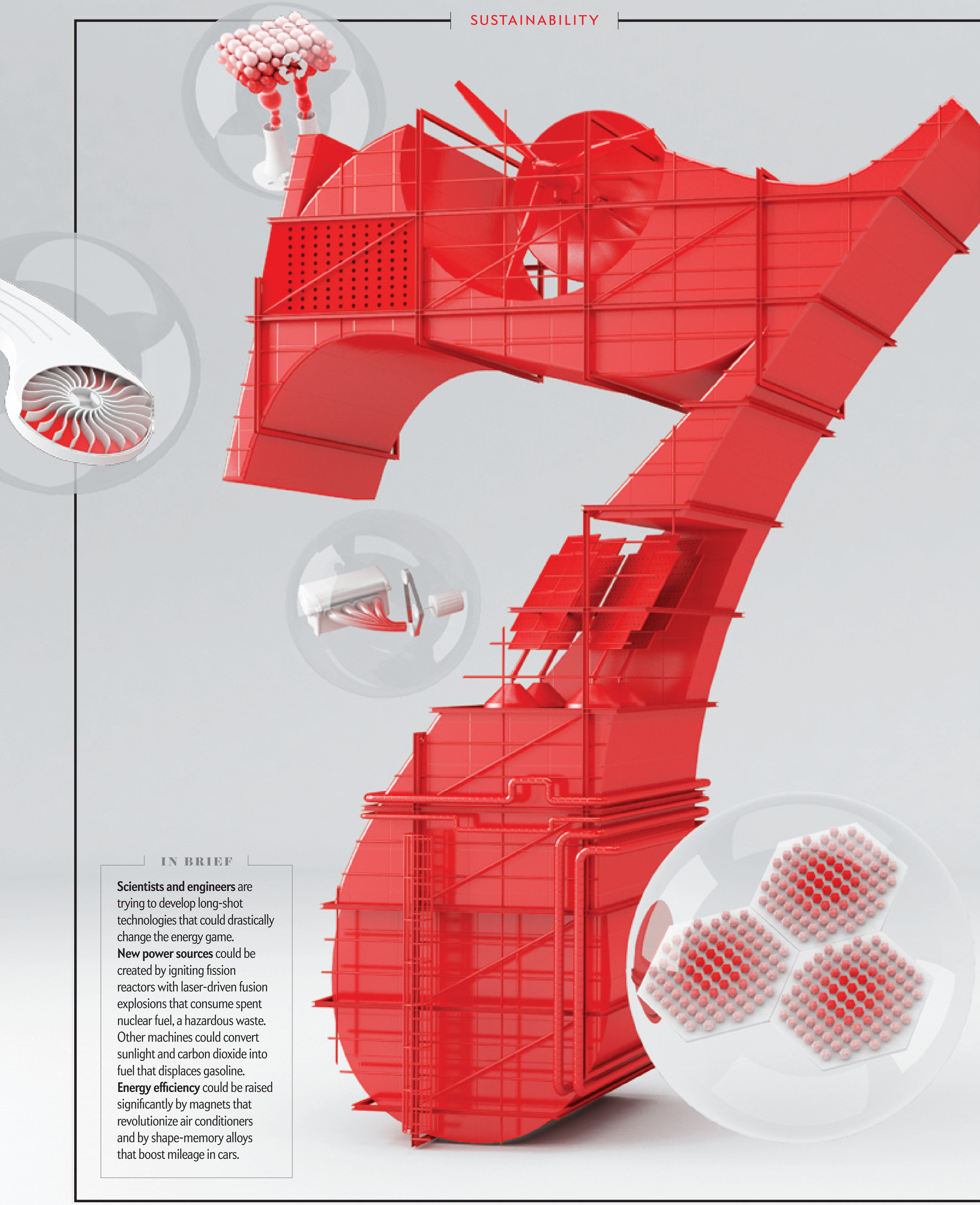
If your junk is too old to resell, you can drop it off at Best Buy, Target or Radio Shack. All three accept and recycle old computers, GPS units, TVs, printers, monitors, cables, cell phones, remotes, headphones, and so on. The store even rewards you with an instant discount on a new purchase or a gift card.

Nobody buys a new fridge or alarm clock every other year, because the feature sets of those product categories are mature. Maybe that will happen to our phones and cameras, too; already people are keeping their PCs longer than they did a decade ago.

In the meantime, we can make things better right now, without making anyone sacrifice much. Pressure the manufacturers to boast about their own eco-efforts—and pressure yourself to dump your old gear at Best Buy or Radio Shack. Doing a good deed for the world couldn't get much easier. SA

EASY WAYS TO GET RID OF YOUR OLD GEAR
ScientificAmerican.com/may2011/pogue

Illustration by John Hersey

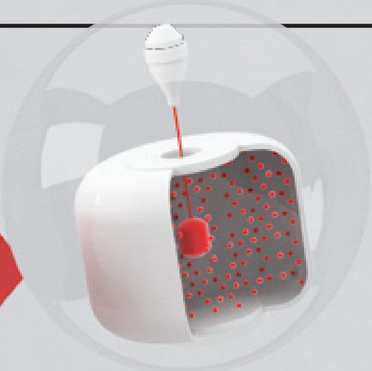


IN BRIEF

Scientists and engineers are trying to develop long-shot technologies that could drastically change the energy game.

New power sources could be created by igniting fission reactors with laser-driven fusion explosions that consume spent nuclear fuel, a hazardous waste. Other machines could convert sunlight and carbon dioxide into fuel that displaces gasoline.

Energy efficiency could be raised significantly by magnets that revolutionize air conditioners and by shape-memory alloys that boost mileage in cars.



RADICAL ENERGY SOLUTIONS

The failure rate may be 90 percent, but if any of these exotic technologies succeeds it could significantly improve energy security and efficiency

MANY PEOPLE ARE WORKING TO HARNESS RENEWABLE ENERGY SOURCES MORE effectively and to enhance energy efficiency. All good. Most of the efforts will probably result in welcomed but incremental improvements, however. Radical innovations are needed to drastically change the energy game.

For years scientists and engineers have touted some fantastic schemes: satellites that beam solar power to receivers on land; wind machines that hover in the atmosphere, generating electricity. Down on earth, however, researchers have recently received substantial government or private funding for a remarkable variety of long-shot technologies in a few key areas. The projects we profile here are leading examples of the payoffs that are possible—if, of course, the inventors manage to overcome daunting hurdles to bringing practical, mass-produced and affordable technologies to fruition.

—*The Editors*

LIKELY TO WORK?

On the following pages, our editors and advisers handicap these technologies in two ways:

LIKELIHOOD of succeeding commercially

POTENTIAL IMPACT on energy supply or use

Lowest ● ○ ○ ○ ○

Highest ● ● ● ● ●

Illustrations by Chris Labrooy

POWER PLANTS

Fusion-Triggered Fission

Lasers coax electricity out of spent nuclear fuel

LIKELIHOOD

POTENTIAL IMPACT

PHYSICISTS AND ENGINEERS HAVE LABORED for decades to harness nuclear fusion, the same process that blazes in H-bombs and the sun. The researchers can readily produce fusion reactions—slamming hydrogen nuclei together fiercely enough that they merge, releasing neutrons and energy. The hard part is doing it so efficiently that the reactions release more energy than used to start them, a condition called ignition, which could ultimately generate electricity.

Scientists at the National Ignition Facility in Livermore, Calif., have therefore come up with a new twist: using fusion to drive fission, the atom splitting that powers conventional nuclear reactors. Director Edward Moses claims the process could lead to prototype power plants in 20 years.

In the Livermore scheme, laser pulses produce fusion explosions at the center of a reaction chamber, emitting neutrons that split atoms in a thick blanket of uranium or other fuel lining the chamber's walls. Energy from these fissioning atoms would multiply the chamber's power output by a factor of four or more. The concept of fusion driving fission for peaceful purposes dates back to Andrei Sakharov, "father" of the Soviet H-bomb, who raised the idea in the 1950s.

If most of the power comes from fission, why not stick with conventional nuclear power plants and avoid the hassle of developing the fusion trigger? A fission reactor relies on a chain reaction in which neutrons from fissioning atoms trigger more atoms to split. Sustaining the chain reaction requires plutonium or enriched uranium fuel, both of which can be used in nuclear weapons.

In the hybrid fusion-fission plant, neutrons from the fusion explosions generate the fission, eliminating the need to sustain a chain reaction. This arrangement broadens the menu of possible fuels to include unenriched uranium, depleted uranium (a voluminous waste product of uranium enrichment) or even spent fuel from other nuclear reactors—waste that would otherwise have to be stored for thousands of years or undergo complicated and hazardous reprocessing for reuse in a fission plant.

Another benefit is the amount of burnup. A conventional reactor splits only a few percent of its fuel's fissionable atoms before the fuel must be changed out. Moses says fusion-fission plants could achieve 90 percent burn, thus requiring perhaps only a 20th as much fuel as a typical fission reactor. An "incineration" phase in the final decade of the plant's roughly 50-year life span would reduce the long-lived waste from 2,500 kilograms or so to about 100, albeit with declining power generation in those years.

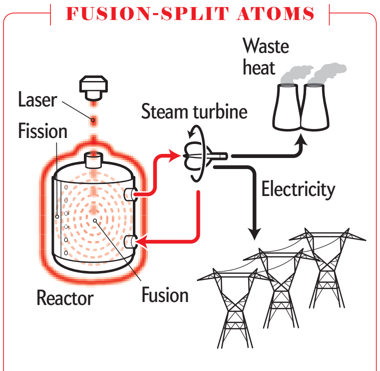
Researchers are also studying fusion-fission proposals based on magnetic fusion, a competitor to laser fusion that bottles the fusion reaction in powerful magnetic fields. In 2009 scientists at the University of Texas at Austin proposed a hybrid reactor with a compact magnetic-fusion trigger. Researchers in China are evaluating designs optimized for producing energy, for breeding conventional reactor fuel and for burning nuclear waste.

Fusion energy of any kind is a radical proposition. Even if Moses's facility demonstrated ignition this year, major technical obstacles would remain before a power plant could become reality. Tiny, exquisitely engineered fusion pellet targets would have to be mass-produced inexpensively. Ignition would have to occur 10 times a second, which requires an array of unproved technology (the National Ignition Facility manages at best a few target shots a day).

Hybrid approaches also require technologies not needed in pure fusion—in particular, the fission blanket, including fission fuels that can withstand a much greater barrage of heat and neutrons than they encounter in a conventional reactor. Proposals range from solid, multilayered "pebbles" to liquids composed of uranium, thorium or plutonium dissolved in molten salts.

The challenges are daunting, and Moses has mapped out an aggressive development path to achieve them. First, though, his facility must prove that laser fusion can actually achieve ignition. —*Graham P. Collins*

FUSION-SPLIT ATOMS



LIQUID FUELS

Solar Gasoline

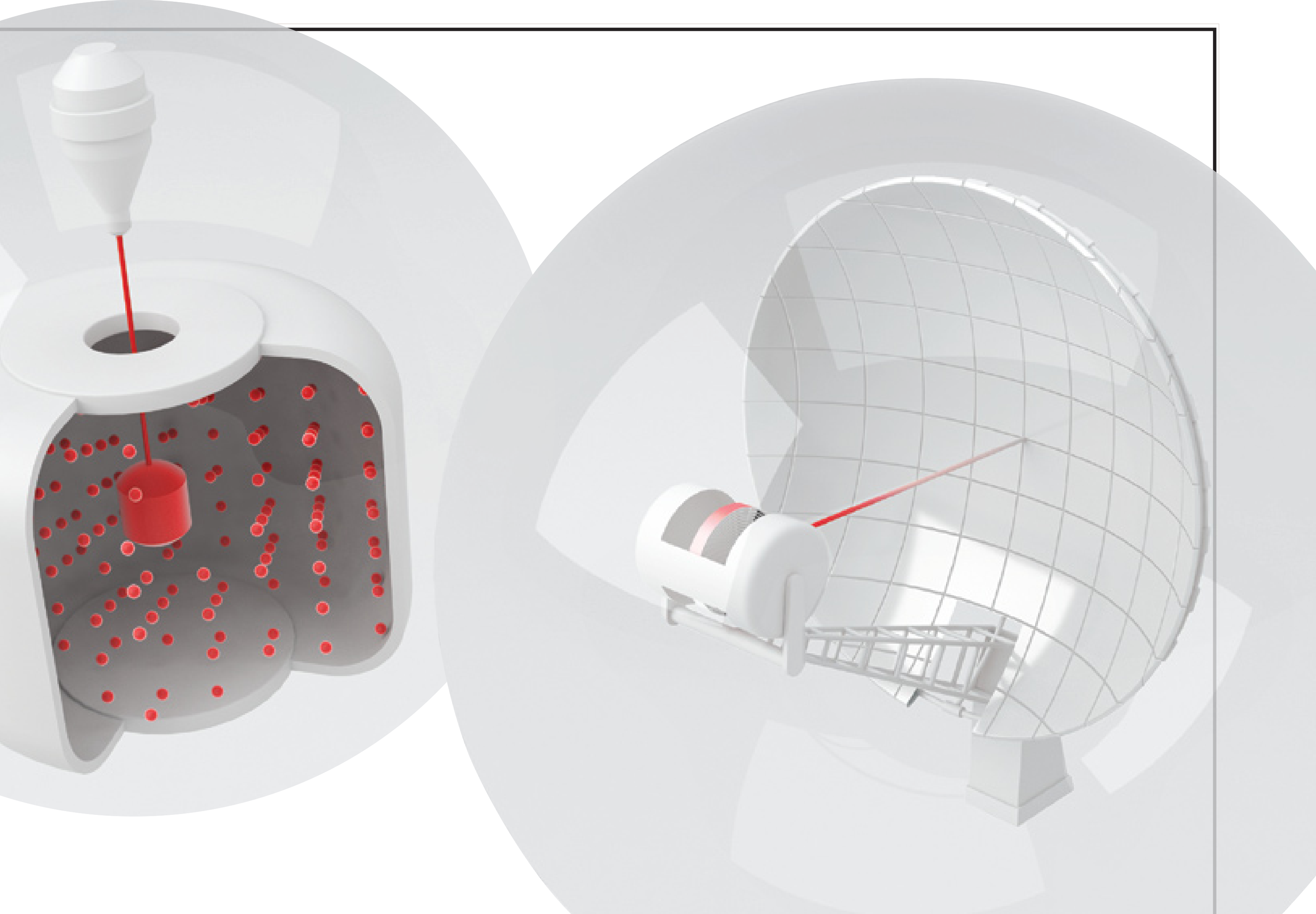
Concentrated sunlight and carbon dioxide propel vehicles

LIKELIHOOD

POTENTIAL IMPACT

THE SUN BATHES THE EARTH IN MORE ENERGY in an hour than civilization uses in a year. If scientists could convert even a fraction of that surplus into a liquid fuel, our addiction to fossil fuels for transportation, and the problems they cause, could end. "Chemical fuels would be the game changer if you could directly make them efficiently and cheaply from sunlight," notes Nathan Lewis, director of the Joint Center for Artificial Photosynthesis at the California Institute of Technology.

Graphics by Brown Bird Design



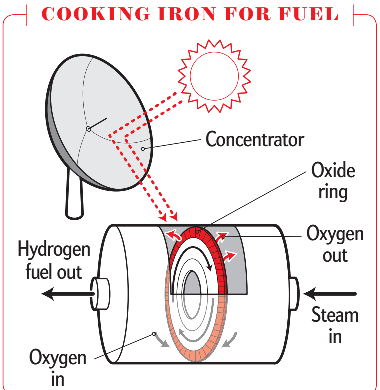
One intriguing effort at Sandia National Laboratories employs a six-meter-wide dish of mirrors in the New Mexico desert. It concentrates the sun's rays on a half-meter-long cylindrical machine shaped like a beer keg that is mounted in front of the dish. The mirrors focus sunlight through a window in the machine's wall on a dozen concentric rings that rotate once a minute. Teeth of iron oxide (rust) or cerium oxide rim the rings and rotate into the beam, heating to 1,500 degrees Celsius. That heat drives the oxygen out of the rust. As the teeth rotate back into the cooler, dark side of the reactor, they suck oxygen back out of steam or out of carbon dioxide that has been introduced into the chamber, leaving behind energy-rich hydrogen or carbon monoxide.

The resulting mixture of hydrogen and carbon monoxide is called synthesis gas, or syngas—the basic molecular building block for fossil fuels, chemicals, even plastics. The process could also absorb as much CO_2 as is emitted when the fuel is burned. Such a system of solar fuels "is like killing four birds with one stone," says Arun Majumdar, director of the Advanced Research Projects Agency–Energy: clean fuel supply, greater energy security, carbon dioxide reduction and less climate change.

Researchers elsewhere, including at the Swiss Federal Institute of Technology in Zurich and the University of Minnesota, are developing syngas-producing machinery. And some start-up companies are pursuing other paths. Sun Catalytix in Cambridge, Mass., dips a cheap catalyst into water and, using electricity from a solar panel, creates hydrogen and oxygen. Liquid Light in Monmouth Junction, N.J., bubbles CO_2 into an electrochemical cell that builds it into methanol. And Lewis himself is building artificial leaves from semiconducting nanowires that absorb sunlight to split water into hydrogen and oxygen.

Of course, overcoming practical problems is the main hurdle. At Sandia, the teeth keep cracking, impeding the reaction. "You're cycling back and forth from 1,500 degrees to 900 degrees; that's a lot to ask of a material," notes chemist Gary Dirks, director of LightWorks at Arizona State University, who is not involved with the work. The next step is to make the rust structure more robust at the nanoscale or to find even better tooth materials. The high cost of the mirrors would also have to drop. Sandia's researchers suggest their syngas engine can make fuel for $10 per gallon ($2.65 a liter). "We haven't proved to ourselves that we can't do it," says chemical engineer and co-inventor James E. Miller, "but we're a long way from doing it." ***—David Biello***

COOKING IRON FOR FUEL



ELECTRICITY

Quantum Photovoltaics

Hot electrons double solar-cell efficiency

LIKELIHOOD

POTENTIAL IMPACT

TODAY'S COMMERCIAL SOLAR CELLS CONVERT only 10 to 15 percent of the light they receive into current, resulting in expensive electricity. One reason is that a single layer of light-absorbing silicon has a theoretical efficiency limit of about 31 percent (the best laboratory cells reach 26 percent). New research into semiconductor crystals, or quantum dots, could boost the theoretical maximum above 60 percent, blazing a path for products that generate electricity at competitive prices.

In a conventional cell, incoming photons knock electrons loose from the silicon, allowing the electrons to flow freely into a conducting wire, establishing a current. Unfortunately, many of the sun's photons have too much energy; when they strike the silicon, it releases "hot electrons," which rapidly lose their energy as heat and return to their initial state before they are captured by the conducting wire. If hot electrons could be grabbed before they cooled, maximum efficiency could double.

One solution is to slow down how fast the electrons cool, creating more time for them to be captured. Last year chemist Xiaoyang Zhu of the University of Texas at Austin and his colleagues turned to quantum dots consisting of a few thousand atoms each. Zhu deposited lead-selenide dots onto a conducting layer of titanium dioxide, a common material. When he shone a light, the hot electrons took up to 1,000 times longer to lose their heat. Zhu "really showed that this concept is possible," says Prashant Kamat of the University of Notre Dame, who was not involved in the research.

Stalling the electrons is only part of the goal, however. Zhu is now looking for a way to help the conductor convert as many hot electrons as possible into current so the conductor itself does not also absorb them as heat.

Many obstacles remain to a working solar cell. "We need to establish all the physics," Zhu says—exactly how hot electrons cool, how they transfer into conductors. "Once we figure all that out, then we can say what the ultimate materials to use would be." The work, he predicts, "will take a while. But I'm confident we can do it. I want to see these solar cells on my roof." The commercial payoff could be huge. *—JR Minkel*

WASTE RECOVERY

Heat Engines

Shape-memory alloys produce extra power for cars, appliances and machinery

LIKELIHOOD

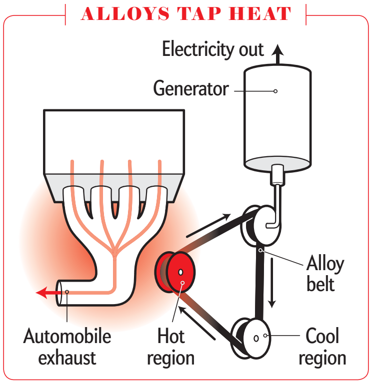
POTENTIAL IMPACT

UP TO 60 PERCENT OF THE ENERGY generated in the U.S. is wasted—much of it lost as heat from millions of vehicles and power plants. Scientists at General Motors in Warren, Mich., are trying to capture this squandered energy using exotic materials called shape-memory alloys, which can convert heat into mechanical energy that in turn generates electricity. Team leader Alan Browne's first target is to recycle heat in a car's exhaust system to power air-conditioning or the radio so that the engine does not have to.

Browne plans to harvest heat with a belt made of thin, parallel strands of nickel-titanium alloy that "remember" a particular shape. All shape-memory alloys flip back and forth between two states: in this case, a stiff "home state" at higher temperature and a more pliable state at lower temperature. In GM's design, the belt is stretched over three pulleys that form corners of a triangle. One corner of the belt would lie close to the hot exhaust system, and another corner would be farther away, where it is cooler. By contracting at the high-temperature corner and expanding at the cooler corner, the belt pulls itself around the loop, spinning the pulleys. The pulleys can turn a shaft that drives a generator. The greater the temperature difference, the faster the loop turns and the more power it generates.

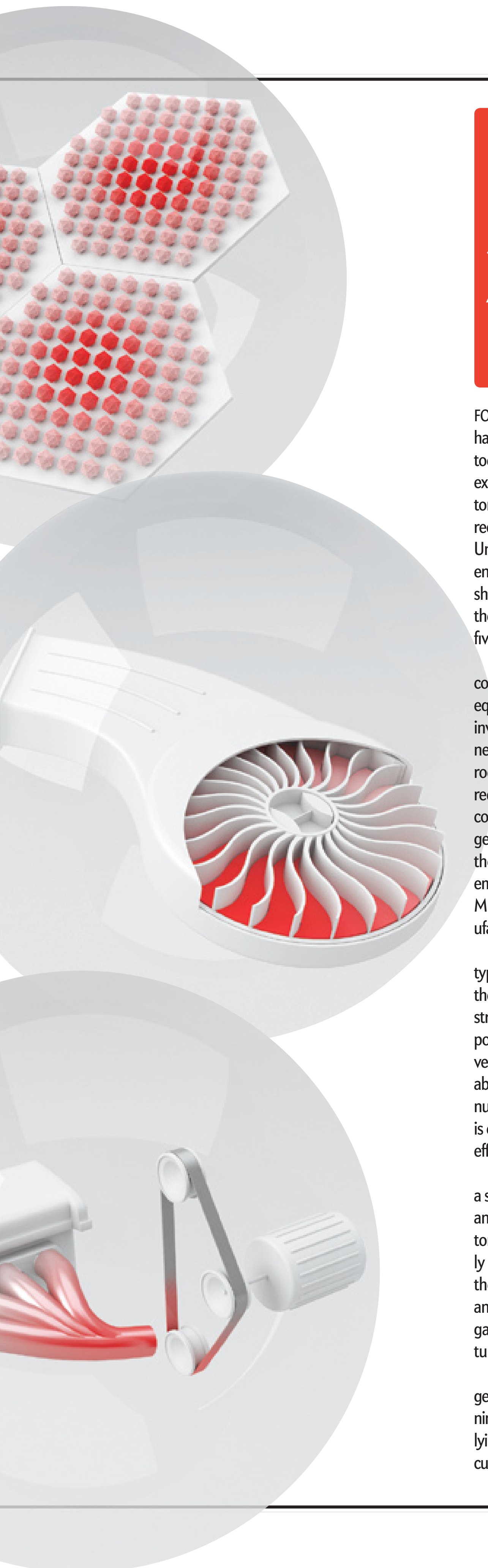
GM's prototype demonstrates proof of principle rather than actual hardware. A small, 10-gram strand yields a modest two watts, enough to power a night-light. Browne claims the technology could be scaled up to hit the marketplace within a decade, adding that no technical issues stand in the way of retrofitting shape-memory-alloy heat engines to household appliances or power-plant cooling towers. The alloys open up a world of applications that were previously considered impractical because they can function in temperature differences of as little as 10 degrees Celsius, explains Geoff McKnight, a collaborating materials scientist at HRL Laboratories.

ALLOYS TAP HEAT



The GM design is straightforward but is still a long shot. Shape-memory alloys suffer from fatigue, becoming brittle. Three months of continuous processing are needed to embed the home-state shape memory. The wires are difficult to join into a belt. Figuring out how to efficiently heat and cool the belt using air is also challenging. Browne is not saying exactly how his team is troubleshooting these issues, except to note that they are varying the gauge of the wire, the belt geometry, and the ways the belt is heated and cooled—every variable "science and man can think of."

GM isn't alone in the quest to recycle heat. Sanjiv Sinha of the University of Illinois is developing flexible, solid-state materials that convert heat into electricity. If heat engines can be built into existing and future hardware, the applications are endless: from thousands of cooling towers and factory boilers to millions of home radiators, refrigerators and chimneys, as well as tractors, trucks, trains and planes. Quintillions of joules could be generated worldwide, slashing fossil-fuel consumption. *—Bijal P. Trivedi*



VEHICLES

Shock-Wave Auto Engine

Gas-turbine cars go five times farther than piston-powered hybrids

LIKELIHOOD

POTENTIAL IMPACT

FOR MORE THAN A CENTURY PISTON ENGINES have powered nearly all cars and trucks. Even today's hybrid vehicles and the new range extenders such as Chevy's Volt use small piston engines to boost power and to efficiently recharge the batteries. But Michigan State University is developing a completely different design, known as a wave-disk engine or shock-wave engine, that eliminates pistons. If the project succeeds, future hybrids could go five times farther on a liter of gasoline.

The compact engine is only the size of a cooking pot and requires considerably less equipment than piston engines, says co-inventor Norbert Müller, a mechanical engineering professor at Michigan State. Pistons, rods and engine blocks are not needed. The reduced mass and higher fuel efficiency could propel "a plug-in hybrid car with regenerative braking as much as five times farther on the same amount of fuel, reducing emissions of carbon dioxide accordingly," Müller says. The system could also cut manufacturing costs by as much as 30 percent.

Müller and his team are testing a prototype wave-disk generator on a benchtop in their East Lansing lab. Their aim is to demonstrate a working, 25-kilowatt (33-horsepower) engine. He expects the energy conversion efficiency of his first machine to be about 30 percent, which trails the 45 percent number set by leading diesel engines. But he is optimistic that improvements could boost efficiency to as high as 65 percent.

In a conventional spark-ignition engine, a spark plug ignites a mixture of gasoline and air inside a chamber, which drives a piston that turns a crankshaft, which ultimately turns the car's wheels. In a diesel engine, the piston powerfully compresses the fuel and air, igniting it. The resulting combustion gases expand, driving the piston backward, turning the crankshaft.

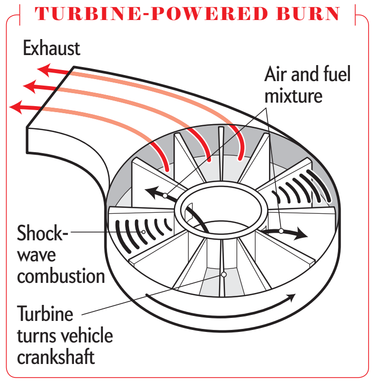
In the wave-disk design, the power-generating process takes place inside a spinning turbine. Imagine a desktop fan (a "rotor") lying horizontal on a tabletop, with many curved blades and a casing around the outer edge. Hot, pressurized air and fuel enter the gaps between the blades from the central spindle. When the high-pressure mixture ignites, burning gases expand in the confined space, forming a shock wave that compresses air in the remaining space. Subsequent reflections of the shock wave off the casing further compress and heat the air, which at the right moment is released through the casing. The force of the pressurized gases on the curved blades, plus that of the escaping gas jets, drives the rotor around, which spins a crankshaft.

Engineers began studying wave-rotor machines as early as 1906, according to the wave disk's other co-inventor, Janusz Piechna, an associate professor at the Warsaw University of Technology in Poland. They are already used in superchargers in some sports cars. The difficult part, however, is knowing how to manage the unsteady gas flows. Predicting the highly complex, nonlinear behavior of these intermittent flows requires detailed numerical calculations, which until recently were too time-consuming or imprecise to pursue, Müller says. High-fidelity simulation carried out at Michigan State and elsewhere is now guiding the precise shaping of the blade geometries and the split-second timing of the combustion to extract the best performance.

Whether computer models can lead to practical road machines remains unclear. "Wave-rotor technology can be rather difficult to implement," says Daniel E. Paxson, who designs flow models at the NASA Glenn Research Center in Cleveland. The Michigan State project "definitely pushes the envelope," he notes with a combination of pragmatic skepticism and admiration. "Whatever the ultimate results, I'm sure they'll learn a lot."

Müller seems to have little doubt that if his team builds the wave-disk generator just right it could find its way into greener hybrid vehicles, from motor scooters to family sedans and delivery trucks. "It's just a matter of time, effort and imagination—and money, of course." *—Steven Ashley*

TURBINE-POWERED BURN



APPLIANCES

Magnetic Air Conditioners

Unusual alloys keep rooms cool and food cold

LIKELIHOOD

POTENTIAL IMPACT

AIR CONDITIONERS, REFRIGERATORS AND freezers help cool our lives, but they burn through energy, consuming up to a third of the electricity used by U.S. homes. A radically different technology that relies on magnets could dramatically cut the load.

Most commercial coolers compress and decompress a refrigerant gas or liquid through a repeating cycle. As the refrigerant cycles, it draws heat out of the inside of a room or appliance. Compressors are energy hogs, however. And the most commonly used gases, when released, warm the atmosphere at least 1,000 times more than carbon dioxide does, molecule for molecule.

Researchers at Astronautics Corporation of America in Milwaukee are developing a cooler based on magnets that eliminate the compressors. All magnetic materials heat up to some extent when exposed to a magnetic field and cool down when the field is removed, a trick known as the magnetocaloric effect. Atoms store heat as vibrations; when a magnetic field aligns the electrons in a metal and keeps them from moving freely, the metal atoms vibrate more, heating up. Remove the field, and the temperature drops. This phenomenon was discovered in 1881, but it has been ignored for commercial purposes because, in theory, cryogenically cooled superconducting magnets would be needed to maximize the effect. In 1997, however, materials scientists at the U.S. Department of Energy's Ames Laboratory in Iowa, collaborating with Astronautics, hit on an alloy of gadolinium, silicon and germanium that showed a giant magnetocaloric effect at room temperature. The company has since found other such alloys.

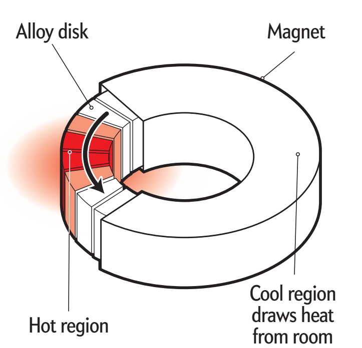
Astronautics is now designing an air conditioner aimed at cooling an apartment or house of about 1,000 square feet. A small, flat disk contains porous wedges made of one of the alloys. The disk is surrounded by a stationary, ring-shaped permanent magnet that lies in the same plane. The magnet has a gap in one side that concentrates the field there. As the disk spins, each magnetocaloric wedge passes the gap and heats up, then cools after it continues on. Fluid circulating inside the system is heated and cooled by the rotating wedges, and the cooled fluid draws heat from the room. The magnet is carefully designed to prevent the field from straying outside the machine, so it does not affect nearby electronics or people with pacemakers.

In conventional coolers, the compressor does most of the work. In magnetic coolers, the motor that spins the wheel does most of the work, and motors are typically far more efficient than compressors. Astronautics aims to have a prototype by 2013 that slashes electricity use by one third for the same amount of cooling provided. A big bonus: the unit uses only water to transfer heat, "and you can't get more environmentally friendly than that," says Steven Jacobs, manager of Astronautics's technology center.

The design could be adapted to refrigerators and freezers, although a lot of complexities must be mastered just to complete a successful prototype. Controlling how the water flows through the porous wedges is tricky; the disk spins 360 to 600 times per minute. Also, the magnet is made from an expensive neodymium-iron-boron alloy, so making it as small as possible while still providing a strong magnetic field will be a commercial necessity. "It's a high-risk technology, but it's got huge potential, and that level of performance is a reasonable target," says mechanical engineer Andrew Rowe of the University of Victoria in British Columbia.

Researchers are experimenting with other unusual cooling technologies. Sheetak, a firm in Austin, Tex., is developing a cooler that does away with refrigerants altogether, instead relying on so-called thermoelectric materials that get cold on one side and hot on the other when electrified. One way or another, consuming less fuel and reducing global warming emissions could leave the world a cooler place. *—Charles Q. Choi*

COOL AIR FROM MAGNET



LIKELIHOOD

POTENTIAL IMPACT

EMISSIONS

Clean(er) Coal

Salt sucks carbon from smokestacks

COAL IS THE CHEAPEST AND MOST PLENTIFUL energy resource in the U.S.—and as the most carbon-heavy source, a major driver of climate change. Engineers have devised various ways to strip carbon dioxide out of a coal plant's exhaust before it enters the atmosphere, but the processes sap up to 30 percent of the energy created by burning the coal in the first place. That burden can double the cost of electricity generated, which makes clean-burning coal a tough sell.

The idea is so appealing, however, that the Department of Energy's Advanced Research Projects Agency–Energy, along with other agencies, has been doling out seed money for research into technologies that might drive down that unacceptable percentage.

One especially enticing design, from the University of Notre Dame's Energy Center, uses a novel material called an ionic liquid—essentially a type of salt. Its first advantage is that it pulls in twice as much carbon dioxide as other, chemically similar carbon absorbers. Another plus is that in doing so, the salt undergoes a phase change from solid to liquid. The change releases heat, which is recycled to help drive the carbon out of the liquid so that it can be disposed of.

"Our modeling shows that we should be able to reduce the parasitic energy to 22 or 23 percent," says Joan F. Brennecke, a chemical engineer and director of the energy center. "Ultimately we'd like to get it down to 15 percent." Her team is building a laboratory-scale unit to demonstrate the technology.

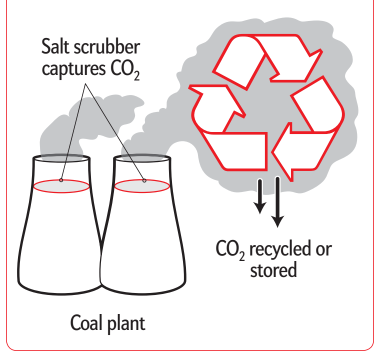
If the approach sounds theoretical at this point, it is. "This is a radical idea," Brennecke admits, "because these materials are totally new," discovered barely two years ago. Brennecke's group is just beginning to explore them, and unexpected problems could crop up at any stage. Even if the process works in the lab, it could prove impossible to scale up to the power plant level.

Furthermore, if the stripping process does work, the carbon then has to be stored somewhere. The leading idea espoused by scientists is to inject it underground, in porous rock formations—a process known as sequestration that has been field-tested but not proved on a large scale. A more experimental notion is to mix the CO_2 with silicates, reproducing the natural process that binds CO_2 into carbonate rock, rendering it inert.

Also to be confronted are the health and environmental issues that go along with coal mining and with disposing of the toxic ash left over after burning. The many problems make environmentalists see red when they hear the phrase "clean coal." Still, coal is so abundant and cheap that if a high-risk idea works out it could make a big difference in the fight against climate change.

—Michael Lemonick

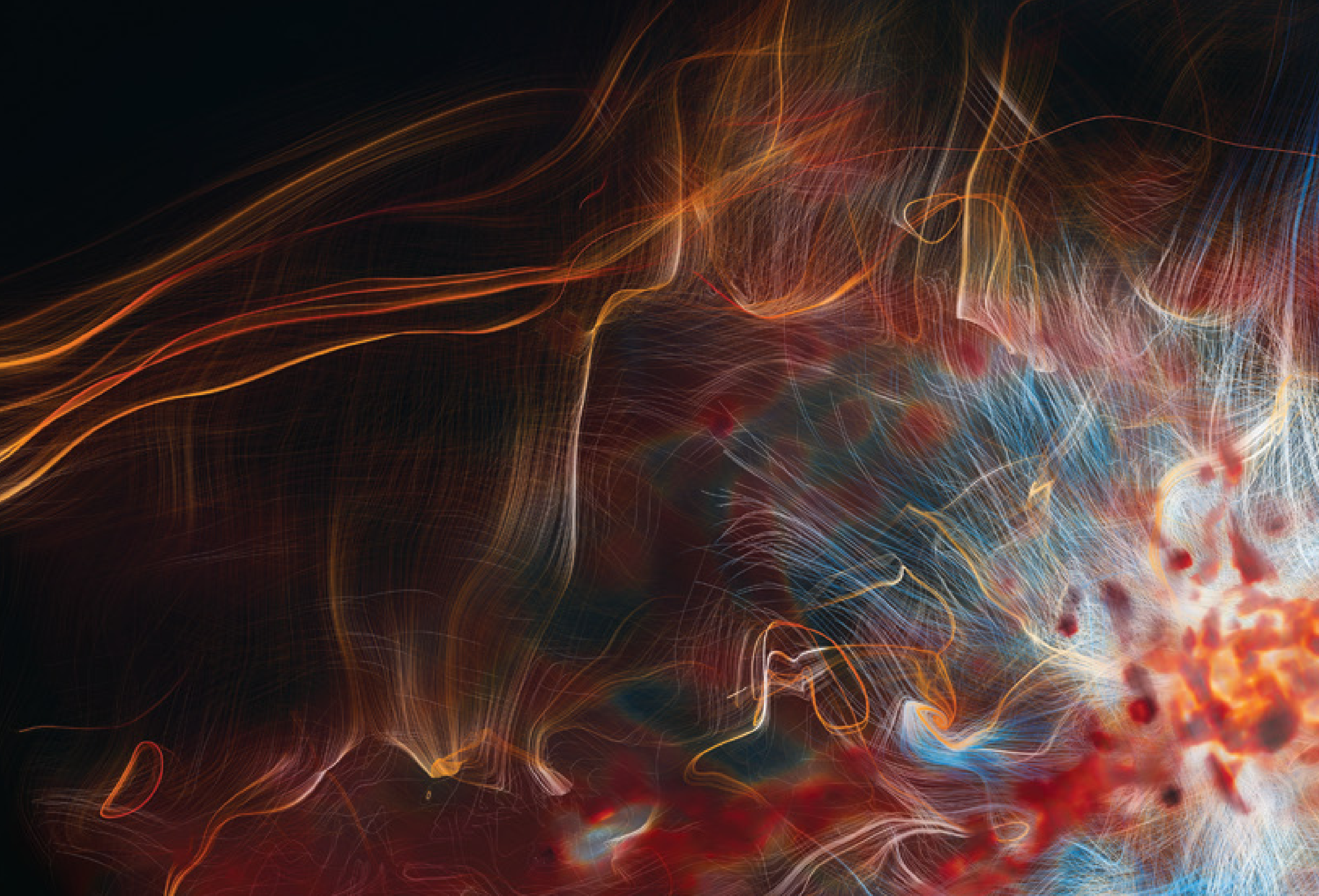
STRIP OUT THE CARBON



MORE TO EXPLORE

Radical projects being funded by the U.S. Department of Energy's ARPA-E program: http://arpa-e.energy.gov
Fusion-triggered fission: https://lasers.llnl.gov/about/missions/energy_for_the_future/life
Quantum photovoltaics: www.utexas.edu/news/2010/06/17/quantum_dot_research
Solar fuels: http://pubs.acs.org/doi/abs/10.1021/bk-2010-1056.ch001
Shock-wave engines: www.nextbigfuture.com/2009/10/wave-disc-engines.html

SCIENTIFIC AMERICAN ONLINE
More exotic technologies are at ScientificAmerican.com/may2011/radical-energy



COSMOLOGY

the lost GALAXIES

By the latest estimate, the observable universe contains 200 billion galaxies. Astronomers wonder: Why so few?

By James E. Geach

IN BRIEF

Forget dark matter: even the supposedly normal matter of the universe is mysterious enough. Why does only a small fraction of it reside in galaxies? Where did the rest go?

The current best guess is that the bulk of the normal matter is trapped in giant gaseous filaments. This so-called warm-hot intergalactic medium, or WHIM, is hard to detect directly.

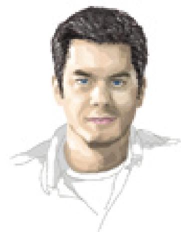
Galaxy formation is evidently rather inefficient. As material falls into a galaxy, the galaxy tends to shoot much of it straight back out again—a process known as feedback.

The atoms in your body have probably been cycled through intergalactic space. Indeed, galaxies and their contents are not fixed structures but the bright tips of a wider sea of gas.

Graphic by James E. Geach and Rob Crain

IN THE THROES OF FORMATION, a galaxy like our Milky Way pulls in dense, cold gas (*red streams*) and also ejects hot gas (*blue streams*) back into intergalactic space. The galaxy ends up with only a small fraction of the raw material. The author and his colleagues generated this image using a state-of-the-art cosmological simulation code.

James E. Geach is an observational astronomer who studies galaxy evolution, particularly their star-formation histories and the evolution of their cold gas. He traces his love of astronomy to the dark night skies of his native Cornwall, England. He is now a postdoctoral researcher at McGill University, where he lives with his wife, Kristen, and their young beagle, Darwin.



I HAVE ALWAYS BEEN STARTLED AND FASCINATED BY THE sandlike abundance of galaxies sprinkled across the night sky. The most sensitive optical image ever made by human beings, the Hubble Ultra Deep Field, captures some 10,000 galaxies in an area about 1/100th the size of the full moon. Scaled up to the whole sky, such a density implies a total of 200 billion or so galaxies. And those are just the most luminous ones; the true number is probably much larger.

How did all those galaxies come to be? This question inspired me to become an astronomer and has been the focus of my research career. Over the years my naive way of looking at galaxies has changed. To judge by their sheer numbers, nature appears to be quite good at producing galaxies. Not so. If you add up all the visible matter in galaxies today, you get only about a tenth of the total endowment created by the big bang. Where is the rest, and why did it not end up in galaxies? These are two of the biggest puzzles in astronomy today.

This missing matter is different from dark matter and dark energy. Those are substances of unknown composition that together amount to 96 percent of the total mass of the cosmos. In the case of numbers of galaxies, the trouble is with the 4 percent that was supposed to be well understood. This slice of the universe is normal matter, made of the same stuff as our bodies and everything around us—primarily baryons, the class of particle that includes protons and neutrons. For the majority of it to go missing is a mystery inside a mystery. Not only is most of the matter in the universe dark and unexplained, but of the small sliver that is normal, only a fraction is accounted for.

Another way to put it is that the process of galaxy formation must be inefficient. It is as if a farmer sowed an entire field of seeds and only one of every 10 germinated. Astronomers have struggled for years to explain how that could be. The emerging answer requires us to revise our notions not only of how galaxies form but of what a "galaxy" even is. One expects not to fathom exotic types of matter; it is rather more disturbing to learn that we still do not grasp the mundane sort.

HONEY, WE LOST HALF THE UNIVERSE

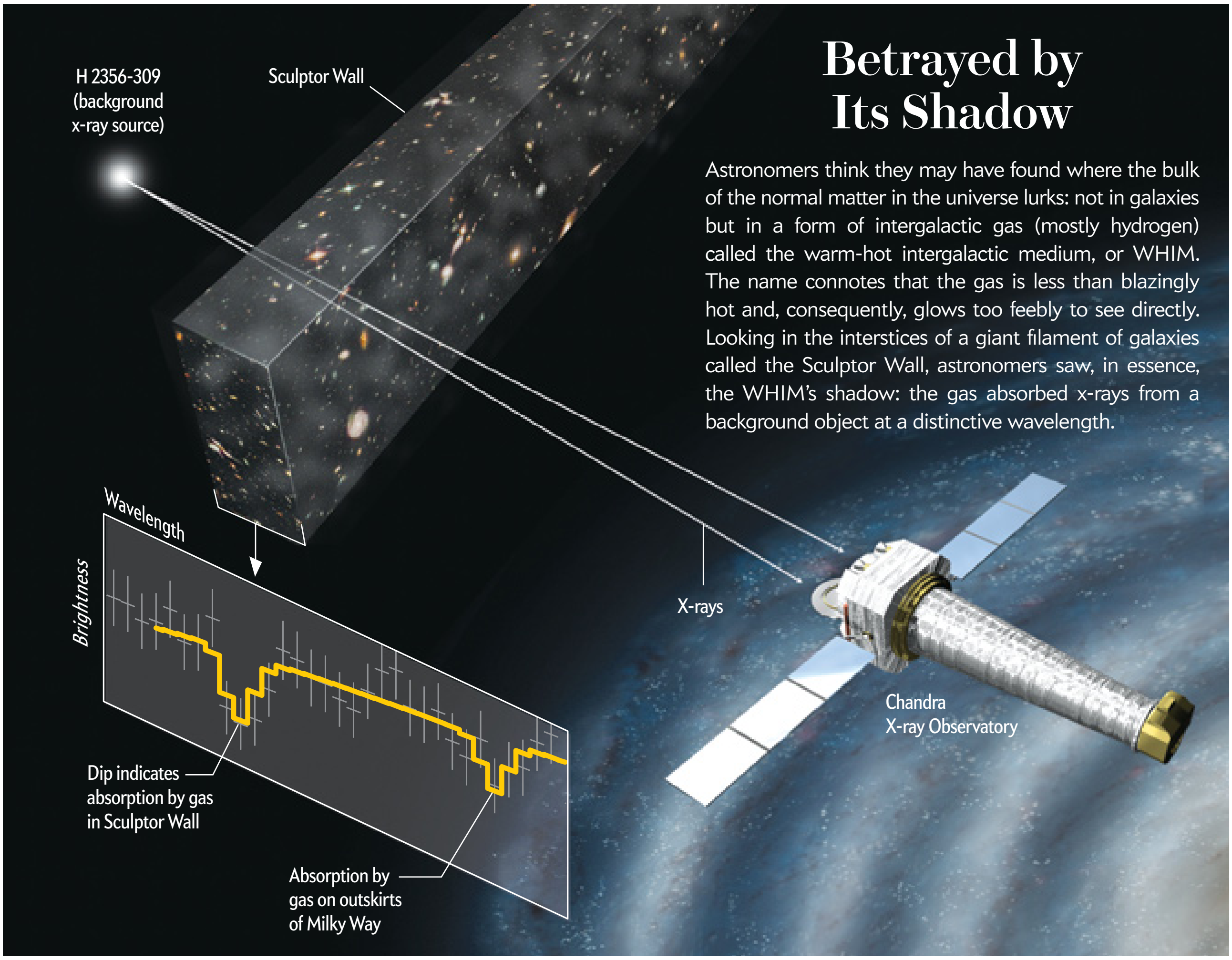
FOR DECADES observers have been piecing together a timeline of cosmic history that describes the content of the universe at different stages in its evolution. In the process, it has gradually become apparent that more baryons were present at the dawn of the universe than we can directly detect today.

The initial amount of baryonic matter is actually fairly straightforward to estimate. This information is encoded into the relic radiation from the big bang: the cosmic microwave background radiation. State-of-the-art experiments such as the Wilkinson Microwave Anisotropy Probe and the Planck space observatory detect small fluctuations in the temperature of this radiation, and the distribution of these fluctuations reflect the baryon density of the universe at a time when galaxies were yet to form. An independent check comes from measurements of the abundances of helium, deuterium and lithium. These elements were synthesized in the first few minutes of the universe in relative amounts that depended on the overall quantity of baryonic matter. Both techniques imply that the total amount of baryonic matter should account for 4 percent of the mass of today's universe.

At the outset, all baryons took the form of a hot gas that filled space. In the regions where the initial matter density was high, gravity caused gas to clump into progressively denser clouds, which were the starting point for galaxy formation. Astronomers have detected this reservoir of gas in the early universe by analyzing the light detected from bright, distant quasars. What quasars are is not important for now; just consider them extremely bright lighthouses, acting as backlighting for the primordial gas floating around in intergalactic space. When a light ray from a quasar passes through a cloud of cold, neutral hydrogen, the gas absorbs some of the photons. Because the gas absorbs only photons of a certain energy, it imprints a telltale dip in the quasar's spectrum at a very specific wavelength: what astronomers call an absorption line.

A ray of light from the quasar might pass through hundreds of such clouds on its journey through the universe, and each one can imprint an absorption line at a slightly different wavelength, depending on the cloud's distance from the observer. By summing up the dips, we can calculate how many of the baryons were locked into these clouds. The result suggests that as late as five billion years after the big bang, or about nine billion years ago, the initial allotment of baryons could still be accounted for. Most were floating around in intergalactic space and had not yet collapsed into luminous galaxies [see "The Emptiest Places," by Evan Scannapieco, Patrick Petitjean and Tom Broadhurst; SCIENTIFIC AMERICAN, October 2002].

In the intervening nine billion years, most of the galaxies we



Betrayed by Its Shadow

Astronomers think they may have found where the bulk of the normal matter in the universe lurks: not in galaxies but in a form of intergalactic gas (mostly hydrogen) called the warm-hot intergalactic medium, or WHIM. The name connotes that the gas is less than blazingly hot and, consequently, glows too feebly to see directly. Looking in the interstices of a giant filament of galaxies called the Sculptor Wall, astronomers saw, in essence, the WHIM's shadow: the gas absorbed x-rays from a background object at a distinctive wavelength.

SOURCE: "CONFIRMATION OF X-RAY ABSORPTION BY WARM-HOT INTERGALACTIC MEDIUM IN THE SCULPTOR WALL," BY TAOTAO FANG ET AL., IN *ASTROPHYSICAL JOURNAL*, VOL. 714, NO. 2; APRIL 22, 2010 *(graph)*

see today formed, wrought from that vast reservoir of primordial hydrogen. Once inside galaxies, baryons were reprocessed and took on various guises: stars, stellar remnants, neutral gas (both atomic and molecular), ionized gas, dust, planets, people. We can audit the mass of baryons in these different forms by measuring their emissions across the electromagnetic spectrum. For example, visible and near-infrared light reveal the mass of stars; a distinctive radio emission line signals the amount of neutral atomic hydrogen; infrared light betrays interstellar dust. In these ways, astronomers have taken a census of all the different phases of baryons in all the galaxies around us, and here is where the discrepancy arises: the total accounts for only 10 percent of the initial inventory of baryons that were present in the early universe. Presumably they did not simply vanish; they linger in the vast spaces between the galaxies. But why can we not see them?

ON A WHIM

ASTRONOMERS KNOW WHERE to find some of these intergalactic baryons. Dense swarms of galaxies called clusters are filled with a diffuse ionized gas, or plasma. The intense gravitational field of the cluster whips ions to high speed, giving the plasma a temperature of hundreds of millions of kelvins, enough to make it glow with x-rays. Space telescopes such as XMM-Newton and Chandra routinely detect clusters of galaxies by means of this x-ray emission. But clusters are rare, so the gas within them accounts for only another 4 percent of the baryons. When we add up all the baryons we can see in galaxies, clusters and elsewhere in intergalactic space, they account for roughly half the total, leaving the equivalent of at least 500 billion galaxies waiting to be found.

To balance the books, Renyue Cen and Jeremiah P. Ostriker, both at Princeton University, Romeel Davé of the University of Arizona, and their collaborators conjectured a decade ago that the missing baryons are out there but have evolved into a phase that is hard to detect. The properties of this elusive component are related to the way that cosmic matter of all types, both mundane and exotic, has developed what astronomers refer to as large-scale structure.

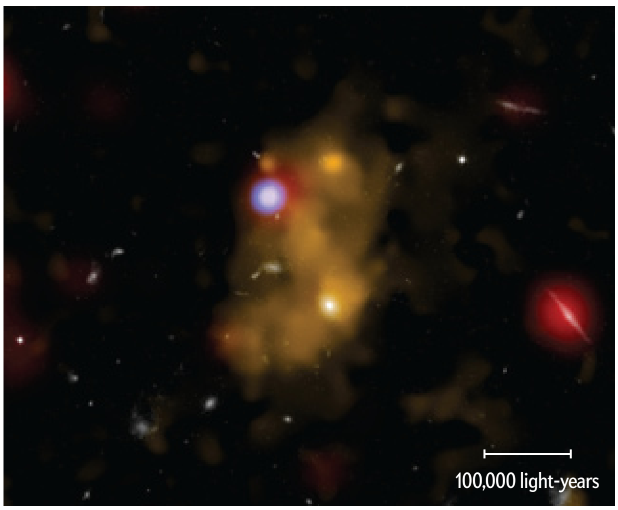
Under the influence of gravity, dark matter has pulled itself into a vast skeletal network that interlaces the universe. Clusters are actually just the high-density nodes of this cosmic web. Outside clusters the majority of galaxies congregate in lower-density groups or line up in long filaments. Intergalactic gas is gravitationally attracted to filaments, and as it falls in, simulations suggest, it gets heated by shock waves to temperatures ranging from 100,000 kelvins to tens of millions of kelvins. That sounds hot but is tepid by the standards of intracluster gas. It is toasty enough to remain highly ionized but too cool to blaze in x-rays.

Illustration by Don Foley

Cen, Ostriker and Davé dubbed this material the warm-hot intergalactic medium, or WHIM. If we could empirically confirm its presence and extent, we might be able to pin down the location and condition of the missing baryons.

The most promising way to detect the WHIM is to look for trace constituents such as ionized oxygen or nitrogen, which absorb ultraviolet light or x-rays of distinctive wavelengths. In fact, astronomers can apply the same absorption-line technique we used for the census of cold hydrogen clouds in the early universe; namely, we can look for dips in the spectra of quasars that backlight the WHIM. We have already had tantalizing glimpses. In the ultraviolet, the Hubble Space Telescope and the now defunct Far Ultraviolet Spectroscopic Explorer (FUSE) have detected absorption by strongly ionized oxygen. The first hints came just over a decade ago, when the concept of the WHIM was still novel. Todd M. Tripp, now at the University of Massachusetts Amherst, and Blair D. Savage of the University of Wisconsin–Madison detected ionized oxygen absorption in the far-ultraviolet spectrum of the quasar PG 0953+415. More observations have followed over the past decade, helped by improvements in detector technology and instrumentation, the most recent being the installation of the Cosmic Origins Spectrograph on Hubble. Although systems with strongly ionized oxygen appear to be plentiful, this ion traces only the relatively cool part of the WHIM. To trace the more abundant hotter gas, we must search for absorption by even more highly ionized species.

Taotao Fang of the University of California, Irvine, and his collaborators, have used the x-ray telescopes Chandra and XMM-Newton to peek into the interstices of the Sculptor Wall, a vast string of galaxies in the local universe—perfect WHIM-hunting territory. They have found absorption by oxygen that is so strongly ionized that it has lost almost all its electrons. The team estimated that the overall baryon density in this WHIM component agreed with cosmological simulations.



Beware of the blob: A wad of hydrogen gas (*yellow*) appears to be the castoff from the formation of a massive galaxy.

COURTESY OF NASA/CXC/J. GEACH ET AL./M. WEISS

Though encouraging, these observations only scratch the surface. The observations are hard: the WHIM signal is weak, and we are generally working at the technical limits of the instrumentation. Even when we do detect absorption, we have to make many assumptions about the makeup of the gas to extrapolate the wider WHIM properties. More important, the absorption-line technique relies on fortuitously placed quasars. Quasars are rare, bright ones even more so, which makes WHIM hunting somewhat of a lottery. Nevertheless, we think we know where the missing baryons are and how they might be detected. Many astronomers are now engaged in efforts to map out the WHIM properly.

THE BATTLE FOR BARYONS

THE EXISTENCE OF THE WHIM goes some way to explaining why galaxy formation is so inefficient. The evolution of large-scale structure made intergalactic gas too tenuous and hot to accumulate into the cool, dense pools required for galaxy formation. Obviously, though, some of the baryons did manage to turn into galaxies, or else we would not be here.

Another thing is clear, too: galaxy formation used to be much more efficient. About eight billion years ago the average birth rate of stars was 10 to 20 times higher than it is today. Most of the galaxies we see today took shape then. To account for why galaxy formation slackened as sharply as it has, astronomers have had to rethink our basic models of how galaxies are born.

In principle, the recipe for a galaxy is quite simple. In a model pioneered in the 1990s by Simon D. M. White of the Max Planck Institute for Astrophysics in Garching, Germany, and Carlos S. Frenk of Durham University in England, galaxies grow within massive clumps of dark matter, termed halos, whose gravitational attraction sucks in surrounding gas like water going down a plug hole. In this model, some of the gas gets heated by shock waves as it plows into the halo and then cools by emitting radiation, allowing it to agglomerate into a cohesive body. Once within the galaxy, the gas can cool further and collapse into clouds of molecular hydrogen. Under gravitational contraction, these clouds can eventually reach the density required to make stars. Bigger galaxies can grow through the mergers of smaller ones.

White and Frenk recognized that their model could not be the entire story, however. For instance, not all of the gas flowing into galaxies would be shock-heated to high temperatures. But the basic picture of gas accretion within dark halos gave astronomers a solid framework within which to understand the principles of galaxy formation. The field has blossomed in the past 20 years. Theorists have explored the physics of gas flow in ever more detail, refining the original model. Recent high-resolution computer models of the thermodynamic evolution of gas in cosmological simulations suggests that some of the gas flowing into young galactic disks in the early universe does so in streams that are relatively cold (10,000 to 100,000 kelvins) and narrow (a few thousand light-years across). These cold flows appear to penetrate the hotter halo gas and directly feed the galaxies.

No one has yet seen this process in action: the detailed physics of the accretion of gas onto galaxies is complicated, and different simulations predict slightly different things. These caveats aside, astronomers now accept that all galaxies build up from the gravitational accumulation of primordial gas, be it gas that heats up and cools down or gas that never heats up at all.

The trouble with this model is that the flow of gas into galaxies cannot go on unabated. If it did, galaxies would grow into monsters, and we know they do not: galaxies today come in only a limited range of masses. Early models seemed to reproduce the observed range of galactic masses pretty well, but in retrospect they worked only because astronomers were using a value for the overall baryon density that was about half the present value. As new measurements of the baryon fraction revised the value upward, theorists fed this information into simulations and realized that their model universes were plagued by a serious overabundance of massive galaxies that are not seen in nature.

Another problem is that models predict a profusion of smallish dark matter clumps that agglomerate into progressively larger bodies. Real galaxies do not follow this pattern. Observers do not see nearly as many small galaxies as the models predict, and the most massive galaxies appear to have formed quickly and efficiently, rather than through the gradual assembly of smaller pieces.

The models were clearly missing a critical ingredient. Something must be regulating the cooling of gas and the formation of stars in galaxies. The process has made small galaxies inefficient at forming stars and limited the size of massive galaxies. Theorists began considering a variety of additional physical processes that would provide this regulation. Known collectively as galactic feedback, these processes can counter, or reverse, the gravitational collapse of gas into galaxies and thus limit the number of stars that can form. They include supernovae explosions, stars' ultraviolet radiation and outflows, and the tremendous energy released during the growth of the supermassive black holes that lurk in the core of all massive galaxies [see "Black Hole Blowback," by Wallace Tucker, Harvey Tananbaum and Andrew Fabian; Scientific American, March 2007]. In the most massive galaxies, black holes are probably the most dominant feedback mechanism; in lower-mass systems, supernovae and stellar winds are more important.

What all these processes have in common is that they inject energy back into the surrounding medium. In this way, galaxies can choke off the inward flow of material, prevent gas that has already accumulated from forming stars or, in extreme cases, eject baryons back into intergalactic space. Simulations that take feedback into account do a much better job of reproducing the observed variety of galaxies. Not only does feedback play a critical role in tuning the evolution of galaxies, it can also resupply, reheat and enrich the WHIM. Through a continuous process of cooling and heating, baryons are cycled between intergalactic space and the stars and gas within galaxies. Galaxy growth is determined by a delicate balance of power that has tipped one way or another over cosmic history. Understanding this battle for baryons revamps our view of galaxy formation.

BLOBOLOGY

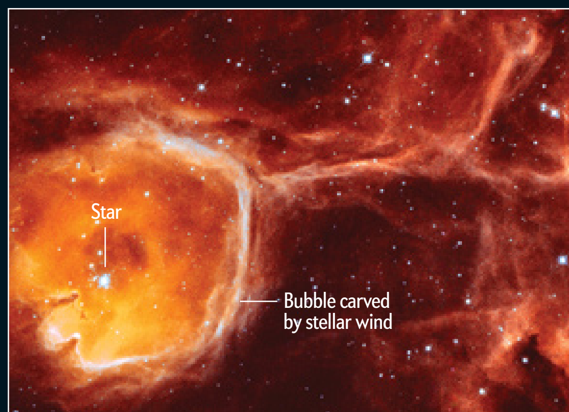
The study of gas cooling and feedback has been a major focus of astrophysics over the past decade. Without empirical data, we have no way of testing the models. Cold material flowing into galaxies in the early universe should give itself away by the diffuse glow that hydrogen emits as it cools. Feedback can be inferred from the bright infrared emission from intense star formation and x-ray or radio emission from the environs of a supermassive black hole. We need to catch both these processes in the act. Recently we may have done just that.

About a decade ago Charles Steidel of the California Institute of Technology and his collaborators discovered a new class of object that appears to tick the boxes for the observational signature of cooling: the Lyman-alpha blob. Never let it be said that astronomers are uptight with their nomenclature; "blob" really is the technical term. Lyman-alpha refers to one of the specific

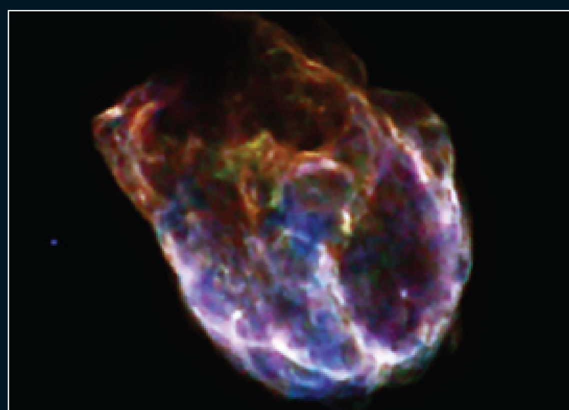
WHAT KEEPS MATTER OUT OF GALAXIES?

Spitting It Back Out

Why do galaxies account for such a small fraction of cosmic matter? Not only does most of the matter end up in the WHIM, but galaxies also limit their own growth. The intergalactic gas that their gravity sucks in coalesces into stars and black holes. These objects feed energy back into the interstellar and intergalactic medium, countering the infall. Feedback processes include the winds blown out by stars, stellar explosions such as supernovae, and jets squirted out by black holes.



STAR



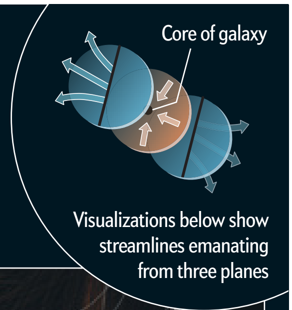
SUPERNOVA

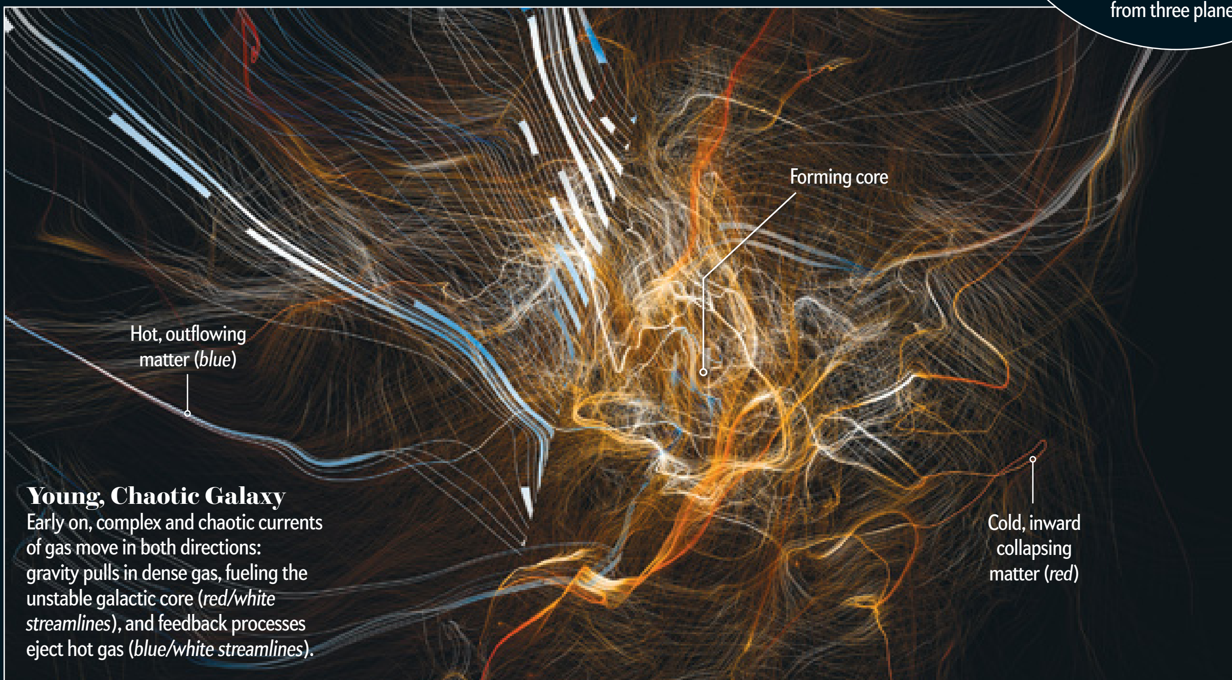
BLACK HOLE

COURTESY OF NASA/ESA/Y. NAZÉ *University of Liège* AND Y.-H. CHU *University of Illinois* (*star*); COURTESY OF NASA/CXC/NCSU/K. J. BORKOWSKI ET AL. (*supernova*); COURTESY OF NASA/CXC/CFA/R. KRAFT ET AL. (*black hole*)

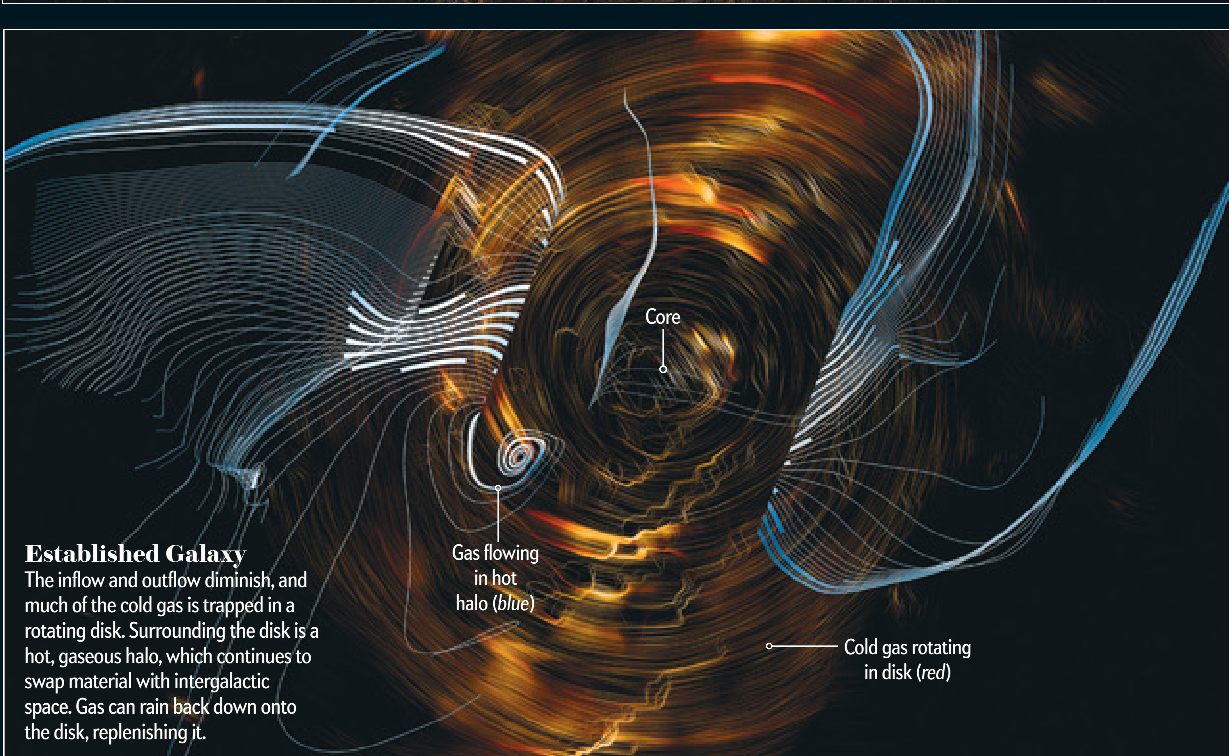
The Turbulent Gyre

Most people think of galaxies as stately structures: giant balls or majestic pinwheels of stars floating in the emptiness of deep space. Astronomers are finding, however, that galaxies are fluid systems that actively exchange material with their surroundings. Normal matter cycles through galaxies, and at any given moment most of it resides in intergalactic space. This simulation shows a galaxy akin to our Milky Way as it would have appeared 10 billion years ago and today.





Young, Chaotic Galaxy
Early on, complex and chaotic currents of gas move in both directions: gravity pulls in dense gas, fueling the unstable galactic core (*red/white streamlines*), and feedback processes eject hot gas (*blue/white streamlines*).



Established Galaxy
The inflow and outflow diminish, and much of the cold gas is trapped in a rotating disk. Surrounding the disk is a hot, gaseous halo, which continues to swap material with intergalactic space. Gas can rain back down onto the disk, replenishing it.

Graphics by James E. Geach

frequencies of light that hydrogen gas emits. These blobs appear to be glowing clouds up to 300,000 light-years across—far bigger than our Milky Way galaxy—making them among the largest luminous objects in the early universe. Astronomers have since discovered scores of them. The observed Lyman-alpha glow bears an uncanny resemblance to theoretical predictions of the radiative signature of cold gas flowing into young galaxies.

On the other hand, many other astrophysical processes could cause Lyman-alpha emission, too. For instance, ultraviolet light or a galactic-scale wind could pump energy into the blobs and cause them to glow. Using Chandra, my colleagues and I have shown that many blobs contain galaxies with actively growing black holes that shine brightly in x-rays. Often this activity is accompanied by intense star formation, revealed by its infrared emission from the obscuring layers of dust that blanket stellar birthing grounds. We have calculated that the energy released by these processes is more than enough to power the Lyman-alpha emission. So perhaps the blobs' glow is caused not by cooling, as many think, but by heating.

Rather than making things clearer, these blobs have muddied the waters somewhat. But that is what excites me about this field—it would not be science if we knew all the answers. We must now devise and conduct new observations to try to unveil what is really going on. Either way, though, blobs are precisely the type of object that could fill in some of the major gaps in our understanding about the origin of galaxies.

The observation that the intergalactic medium surrounding young, active galaxies gets swamped by radiation could help resolve another problem with galaxy-formation models. Very high resolution simulations of dark matter predict that galaxies such as the Milky Way should be accompanied by thousands of lower-mass dwarf galaxies buzzing around them like bees around a hive. Although the Milky Way does have a few dwarf companions, they are far fewer than the simulations predict.

One solution could be that the dwarf galaxies did form in the early universe, but their parent galaxy blasted them with radiation and winds. The barrage stripped away any baryons the dwarfs had managed to accumulate, leaving only barren clumps of dark matter that have skulked on the outskirts of the parent galaxy ever since. Larger galaxies reach a truce in the battle for baryons, but smaller ones lose the battle entirely.

WHAT IS A GALAXY?

PERHAPS THE MOST EXHILARATING experience a scientist can have is the feeling of a sea change in one's perspective on the world. For me, that came when I had to reevaluate what I thought of as "a galaxy." Traditionally we think of luminous galaxies as isolated and discrete island universes, as German philosopher Immanuel Kant put it. In some sense, that is clearly true. But the bright galactic islands of light are just the visible tips of a much wider, but still elusive, sea of baryonic matter. This material pervades the universe, distributed within and shaped by a vast, underlying dark architecture, continuously evolving through gravity.

All those baryons started off in the same state: a hot, pristine gas that rapidly formed the basic elements of hydrogen and helium, along with small amounts of deuterium and lithium. What we think of as galaxies formed from this raw material, pulled into dense concentration by gravity. But these structures are not fixed groups of baryons. Material moves among them as part of a vast cycle that has been in operation since the big bang. The competing influences of gravity and feedback cause gas to cool onto, and later get ejected from, galaxies. Recent computer simulations by Rob Crain of the Swinburne University of Technology in Melbourne, Benjamin Oppenheimer of Leiden University in the Netherlands and their collaborators suggest that up to half of the baryons currently locked into galaxies in the local universe have cycled through the intergalactic medium at least once and often many times. The baryons that make up your body have participated in this cycle for nearly 14 billion years; the matter within your fingernail could have formed in stars in other galaxies and then spent billions of years exiled in intergalactic space before coming to rest in our solar system. You are just an ephemeral phase, a brief host, to this rare substance we call "normal."

This concept of baryon cycling underpins the emerging view of galaxy evolution. The big picture you should have in mind is that galaxy evolution is just a small component of the large-scale evolution of the intergalactic medium. The baryonic universe is predominately gaseous, not galactic. The intergalactic medium is a battleground of forces, and amid this maelstrom, galaxies form.

Matter within your fingernail could have spent billions of years exiled in intergalactic space before coming to rest in our solar system.

Galaxies are just one processing stage in a cycle that is continuously shifting baryons from one phase to the next, and at any one time, most of the baryons in the universe are not inside galaxies.

Sentimentally, perhaps, we hold galaxies in a special regard: the Milky Way is our cosmic habitat, a brilliant, vast, complex home within the darkness. From an anthropic viewpoint, we just happen to be lucky enough to exist at a time when the baryons that make up Earth and everything on it have taken on a cold, stable form. That will not always be the case. The death of the sun around five billion years from now will incinerate the inner planets, evaporate the outer ones and gradually disperse the resulting detritus of heavy elements back into the interstellar medium. Unless humans manage to cheat the cycle by developing the technical capability to escape the confines of the solar system, the ashes of every material thing on Earth are fated to be returned, enriched, to the cosmos. And so the cycle continues. SA

MORE TO EXPLORE

The Search for the Missing Baryons at Low Redshift. Joel N. Bregman in Annual Review of Astronomy and Astrophysics, Vol. 45, No. 1, pages 221–259; September 2007. Preprint available at **arxiv.org/abs/0706.1787**

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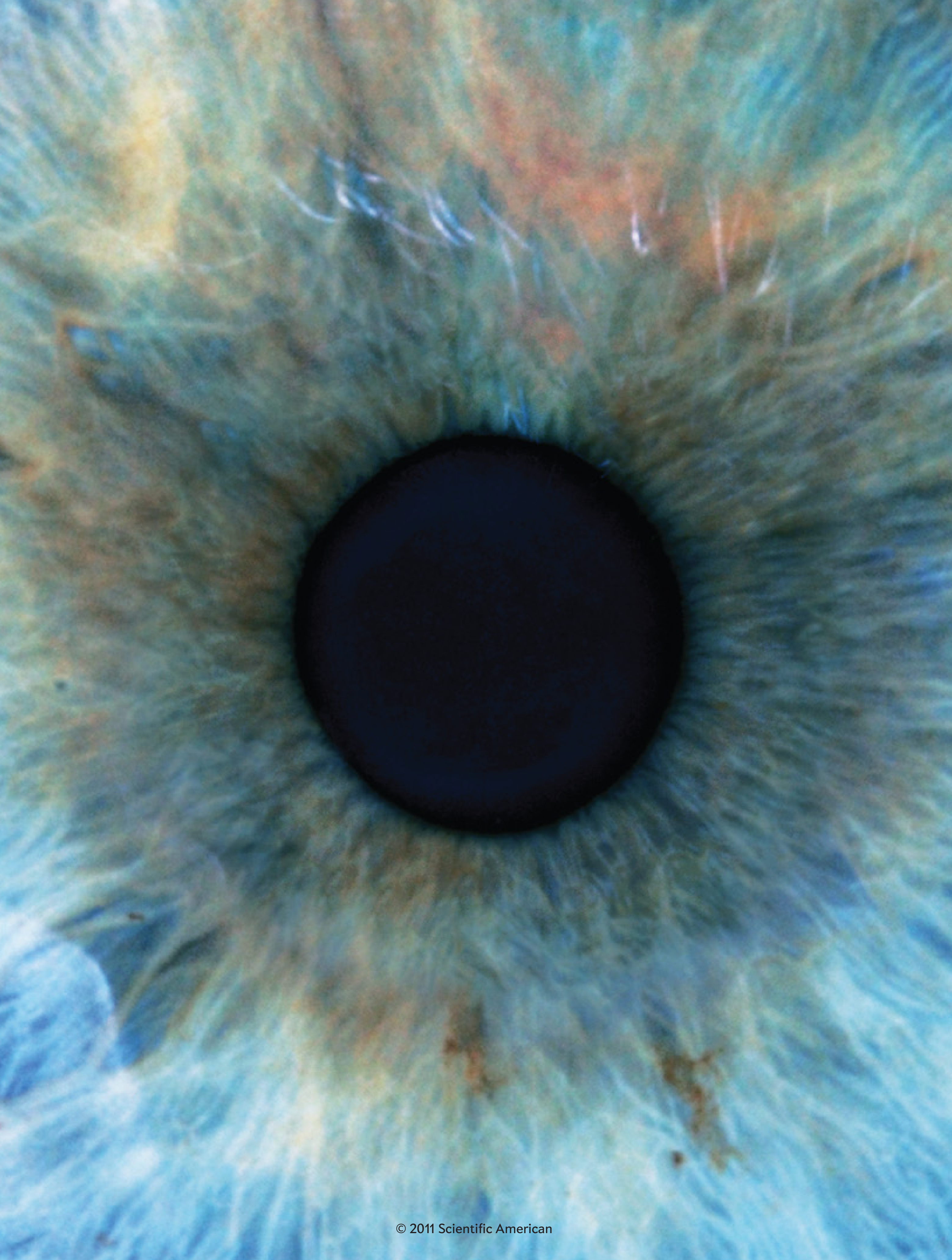
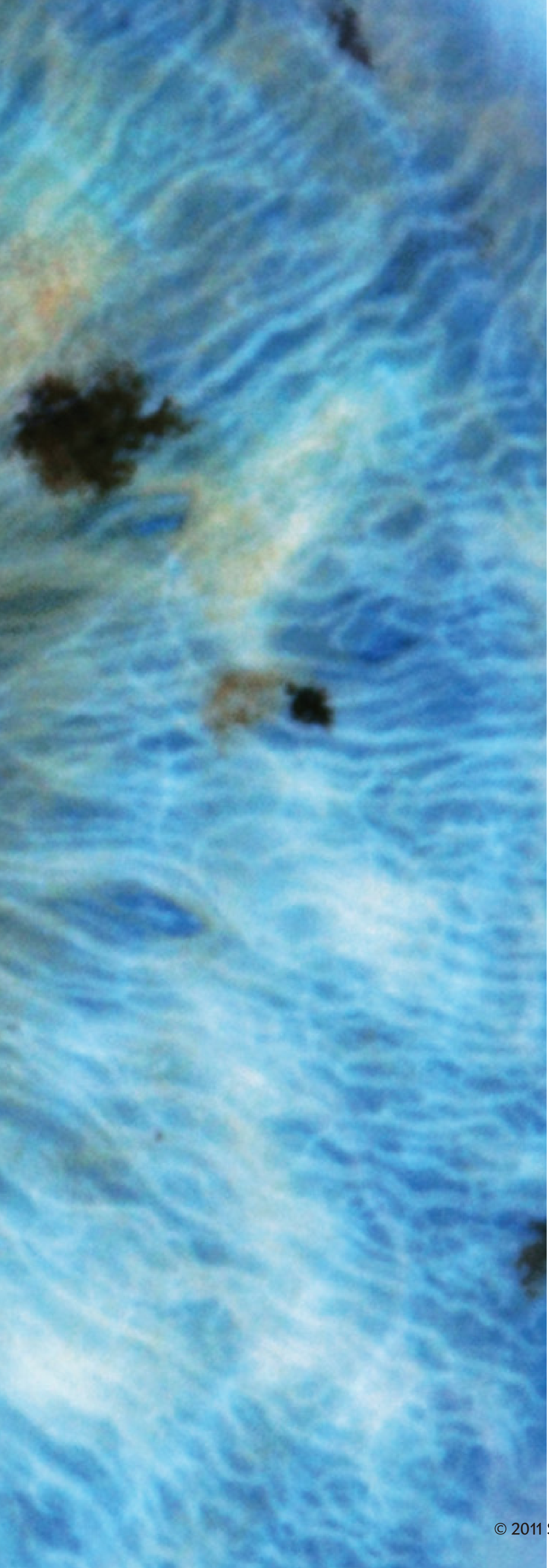
The author's Web site, with images and links: **www.physics.mcgill.ca/~jimgeach**

SCIENTIFIC AMERICAN ONLINE
Get a full 3-D view of a nascent galaxy at **ScientificAmerican.com/may2011/geach**





NEUROSCIENCE

the hidden organ in our eyes

Our bodies adjust to the cycle of day and night thanks to specialized neurons in our eyes. Ongoing study of these cells could lead to new treatments for winter depression and other conditions

By Ignacio Provencio

IN THE 1920S HARVARD UNIVERSITY GRADUATE STUDENT Clyde E. Keeler discovered two surprising facts about mice he had bred in his rented attic room. One, all the progeny were completely blind. Two, despite the animals' blindness, their pupils still constricted in response to ambient light, albeit at a slower rate than did the pupils of sighted mice.

Many years later researchers extended Keeler's observation, showing that mice genetically engineered to lack rods and cones (the light receptors involved in vision) nonetheless reacted to changes in light by adjusting their circadian clock—the internal timer that synchronizes hormone activity, body temperature and sleep. The animals performed the usual daytime activities when in daylight and nighttime activities when in the dark. They could do so even though their retinas lacked the photoreceptor cells that vertebrate eyes use to form images, although surgically removing their eyes abolished this ability. This phenomenon may be common to many mammals, including humans: recent experiments have shown that certain blind people can also adjust their circadian clocks and constrict their pupils in response to light.

One explanation for the apparent paradox is that the photoreceptors within the eye that are required for vision are not responsible for regulating the timing of daily activity; other receptors do that. But until quite recently, the notion that the eyes could possess photoreceptors other than rods and cones seemed absurd. The retina is one of the most thoroughly studied tissues in the body, and the only photoreceptors known to exist in the eyes of mammals were the familiar duo, rods and cones.

The evidence is now very convincing, however, that the eyes of mammals, including those of humans, do have specialized photoreceptors that are not involved in image formation. The light-detecting molecules in these cells are different from those in rods and cones, and the cells connect to different parts of the brain. Thus, just as our ears provide us with our sense of equilibrium as well as with our hearing, each of our eyes is also essentially two organs in one.

The discovery may lead to help for people who have trouble adjusting their biological clocks. Jet lag is the most obvious manifestation of circadian desynchrony—the loss of synchronization between the cycling of day and night and our internal clock. Working the night shift, a self-imposed form of the condition, is thought to raise one's risk of cardiovascular disease, gastrointestinal distress, cancer and metabolic syndrome—a condition that can ultimately lead to type 2 diabetes and stroke. Some of history's most infamous industrial accidents, such as the 1989 grounding of the oil tanker *Exxon Valdez,* the 1984 explosion at the Union Carbide plant (now owned by Dow Chemical Company) in Bhopal, India, and the 1979 near-nuclear meltdown at Three Mile Island, occurred during the night shift, when worker vigilance was compromised. Moreover, millions of people living at extreme northern or southern latitudes suffer from seasonal affective disorder, an often severe form of depression that also appears to be a response to lack of light during short winter days. Better understanding of how the third kind of photoreceptor controls circadian rhythms and emotions is already suggesting ways to minimize the negative effects of jet lag, night-shift work and long winter nights.

LIGHT-SENSING BUT OVERLOOKED

Biologists have long known of organisms that have light-detecting organs for purposes other than image formation. A change in illumination may signal to an animal that it has become exposed, which in turn indicates a vulnerability to predators or potential damage from ultraviolet radiation. Many animals have evolved adaptations, such as active camouflage or avoidance of light, to minimize the consequences of being exposed. Although these adaptations require some system of light detection, they do not require vision per se. For example, in 1911 Austrian zoologist and future Nobel Prize–winner Karl von Frisch recognized that blinded European minnows darkened when exposed to light. Damage to the base of the brain, on the other hand, abolished the response, leading von Frisch to propose the existence of nonvisual photoreceptors in the deep brain.

Many animal species possess such light-sensing cells. Sparrows, for example, can tune their circadian clocks even when deprived of their eyes, as shown in the early 1970s by Michael Menaker, then at the University of Texas at Austin. Follow-up experiments showed that the birds have light-sensing cells in their brain. It turns out that a surprising amount of light can penetrate the feathers, skin and skull of a bird to activate these cells.

The possibility that at least some mammals might also have light receptors not involved in vision first drew the attention of biologists when Keeler reported on his home-bred mice in the 1920s. Because the anatomy of the mammalian retina was so well understood, the assumption was that the missing light-sensing organ must be located somewhere other than in the eyes. But by the early 1980s studies on eyeless rodents by Randy J. Nelson and Irving Zucker, both then at the University of California, Berkeley, seemed to call this hypothesis into question. Those animals were unable to adjust their circadian rhythms to the cycle of night and day, suggesting that the light-sensing receptors had to reside within the eye.

Menaker, who meanwhile had moved to the University of Oregon, set out to investigate whether mouse eyes had a role in light-sensitive responses that do not require the formation of images. He and two of his graduate students, Joseph Takahashi and David Hudson, looked at mutant mice that lacked functional rods and cones, except perhaps for a few minimally active cones. To the researchers' surprise, these blind mice could restrict their activity to the nighttime and remain relatively inactive during the daytime, just as fully sighted mice do.

One possible explanation for this behavior was that the few sickly surviving cones were somehow able to maintain nonvisual responses to light. But in 1999 a team led by Russell Foster, then at Imperial College London, used mutant mice completely lacking rods and cones to show that these cells were not necessary

Ignacio Provencio is an associate professor of biology at the University of Virginia, where he also earned his Ph.D. He developed his interest in neuroscience while studying fireflies, cockroaches and crayfish when he was a student of Jon Copeland at Swarthmore College.

IN BRIEF

Some animals sense light with organs outside their eyes, but humans do not. Still, some blind people can adjust their body to the cycle of night and day.

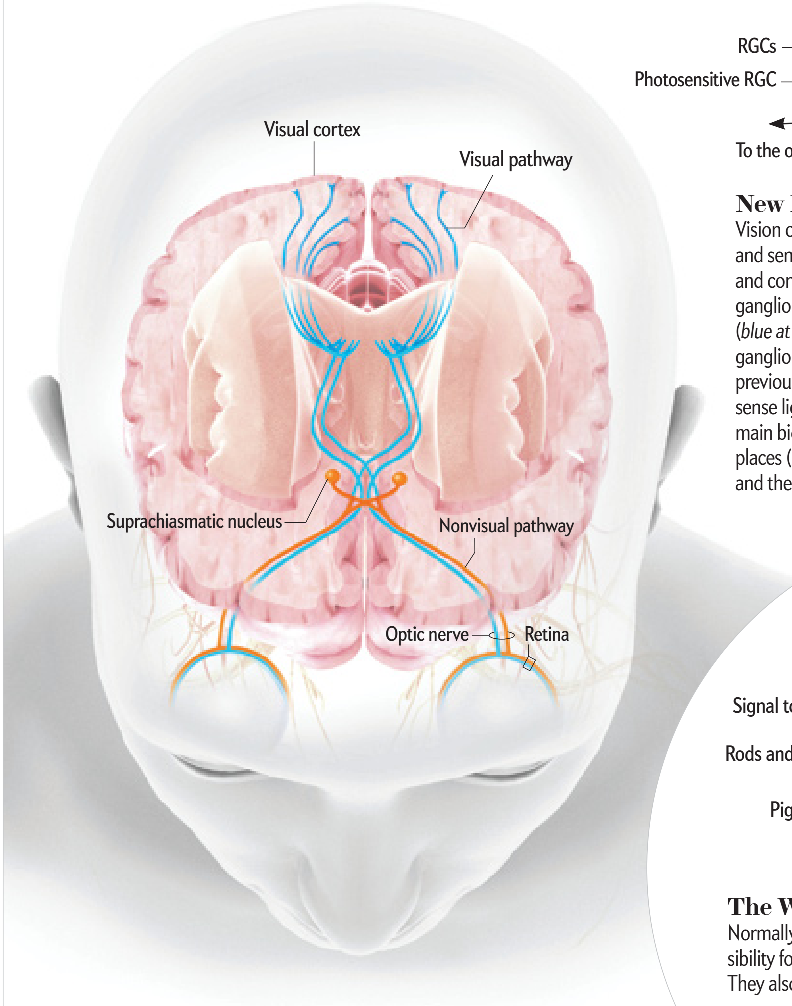
In recent years such nonvisual responses to light have been linked to specialized neurons in the retina that can detect light autonomously but also relay signals from rods and cones, other light-sensing cells. **These neurons** respond to blue light and may be remnants of evolutionarily ancient organs from our invertebrate past.

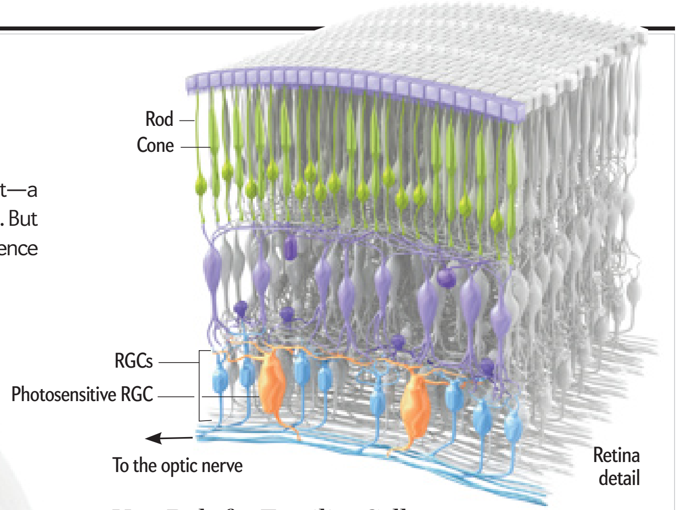
The discovery may lead to new approaches to treating seasonal affective disorder, certain sleep disorders and other debilitating conditions.

CHRISTIAN WEBER *Gallery Stock (preceding pages)*

How the Body Knows Day from Night

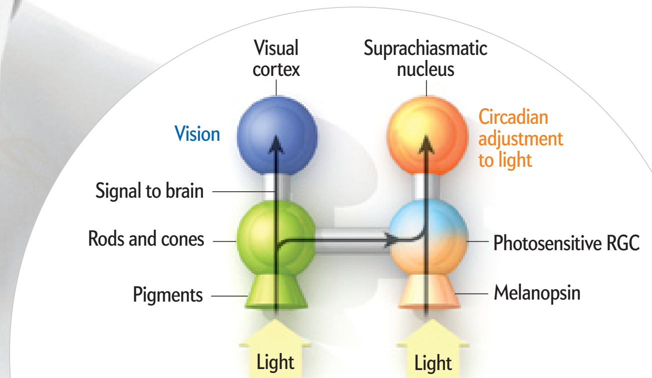
Our biological rhythms naturally adjust to the cycles of day and night—a spontaneous response that can persist even in some blind individuals. But until recently, no one knew which part of the body signaled the difference between day and night to the brain. Scientists now have the answer.





New Role for Familiar Cells

Vision occurs when the rods and cones of the retina detect light and send signals to the visual cortex at the back of the brain. The rods and cones convey the signals to the brain via neurons called retinal ganglion cells (RGCs), which extend their axons down the optic nerve (*blue at left* and *above*). Experiments have shown that a subset of those ganglion cells, known as photosensitive RGCs (*orange above*), produce a previously unknown pigment called melanopsin that enables them to sense light directly. Photosensitive RGCs send information to the brain's main biological clock, the suprachiasmatic nucleus (*left*), among other places (*not shown*). It is as if our eyes were two organs: one for seeing and the other for nonvisual responses to light.



The Wiring

Normally the pigment-containing ganglion cells do not take sole responsibility for collecting light information for the suprachiasmatic nucleus. They also relay information from the rods and cones to that brain area.

for nonvisual responses to light. This finding left only one explanation: the eye must contain a yet to be discovered type of photoreceptor.

This was a heretical proposition. The cells in the retina involved in the formation of images had been known since the mid-1800s. The notion that another light-sensitive cell in the retina had been overlooked for almost 150 years seemed absurd.

PROMOTING HERESY

AND YET RESEARCH MARK D. ROLLAG AND I began in the mid-1990s at the Uniformed Services University of the Health Sciences eventually helped to prove Foster right. Rollag was interested in a different form of nonvisual photoreception: amphibian camouflage. Pigmented cells in the tails of tadpoles darken under light, an adaptive response that helps to conceal the animal when it is exposed. These cells, called dermal melanophores, maintain their response even when removed from the animal and cultured in a dish. Rollag and I identified a novel protein in the cultured cells that is strikingly similar in composition to the class of protein pigments called opsins, which enable rods and cones to detect light. We named the new protein melanopsin.

The similarity with the known opsins strongly suggested that melanopsin was the molecule that triggered the darkening response. Wondering if melanopsin also played a role in other light-detecting cells, we searched for it in other frog tissues known to be directly light-sensitive—such as particular areas of the brain and the iris and retina of the eye. As it turned out, neither rods nor cones contained this new light-sensitive protein. But, to our

Illustration by Bryan Christie

surprise, it did turn up in retinal neurons called retinal ganglion cells that were not previously believed to be light-sensitive.

The vertebrate retina is an elegant three-layered structure. The deepest layer contains the rods and cones, so light must travel through the other layers before it is detected for vision [*see box on preceding page*]. Information from the rods and cones is then transferred to the middle layer, where it is processed by several different classes of cells. Finally, these cells communicate the processed signal to the surface layer, which is primarily composed of ganglion cells. Long, signal-conveying axons extend from these ganglion cells to carry information through the optic nerve and to the brain.

In 2000 my colleagues and I found the first hints that a very small fraction of these ganglion cells were directly sensitive to light. We then discovered that 2 percent of mouse retinal ganglion cells contain melanopsin and that a small percentage of these cells in humans also contain it. In 2002 experiments by David M. Berson and his colleagues at Brown University confirmed our view. They incapacitated the rods and cones and filled the melanopsin-containing ganglion cells with a dye. Next, they removed the retinas from the eyes of the mice and showed that the stained nerve cells fired when exposed to light. Given that the rods and cones were disabled, the response meant that, beyond relaying signals from rods and cones, these particular ganglion cells were able to detect light on their own.

The hypothesis garnered support from evidence found in 2002 by other teams. Samer Hattar of Johns Hopkins University and his co-workers showed that some axons from the mouse retina connect to the suprachiasmatic nucleus—the area of the brain that regulates the body's internal clock—whereas others connect to the area of the brain that controls the constriction of the pupils. And the ganglion cells connected to those areas are precisely the ones that contain melanopsin. All these discoveries pointed to the same solution to our riddle: photosensitive ganglion cells would enable mice with no functioning rods and cones to constrict their pupils and to keep their bodies in tune with the light/

THE EXPERIMENTAL EVIDENCE

Uncovering the Eyes' Double Life

To understand how mammals adjust their circadian rhythms to the cycle of night and day, researchers engaged for decades in a kind of experimental whodunit, testing what happened when various parts of the eye were disabled. They soon found that rods and cones were not critical but that something else in the eye had to be (*second and third panels*). When melanopsin was detected in a subset of retinal ganglion cells and shown to be light-sensitive, that pigment was thought to be key, but then it, too, proved inessential (*fourth panel*). Further tests (*last panels*) showed that this subset of ganglion cells is necessary but that the system has built-in redundancy. If ganglion cells that usually contain melanopsin lack it, circadian rhythms will persist as long as the rods and cones still function. If rods and cones do not work, the melanopsin in the ganglion cells can provide the needed signals.

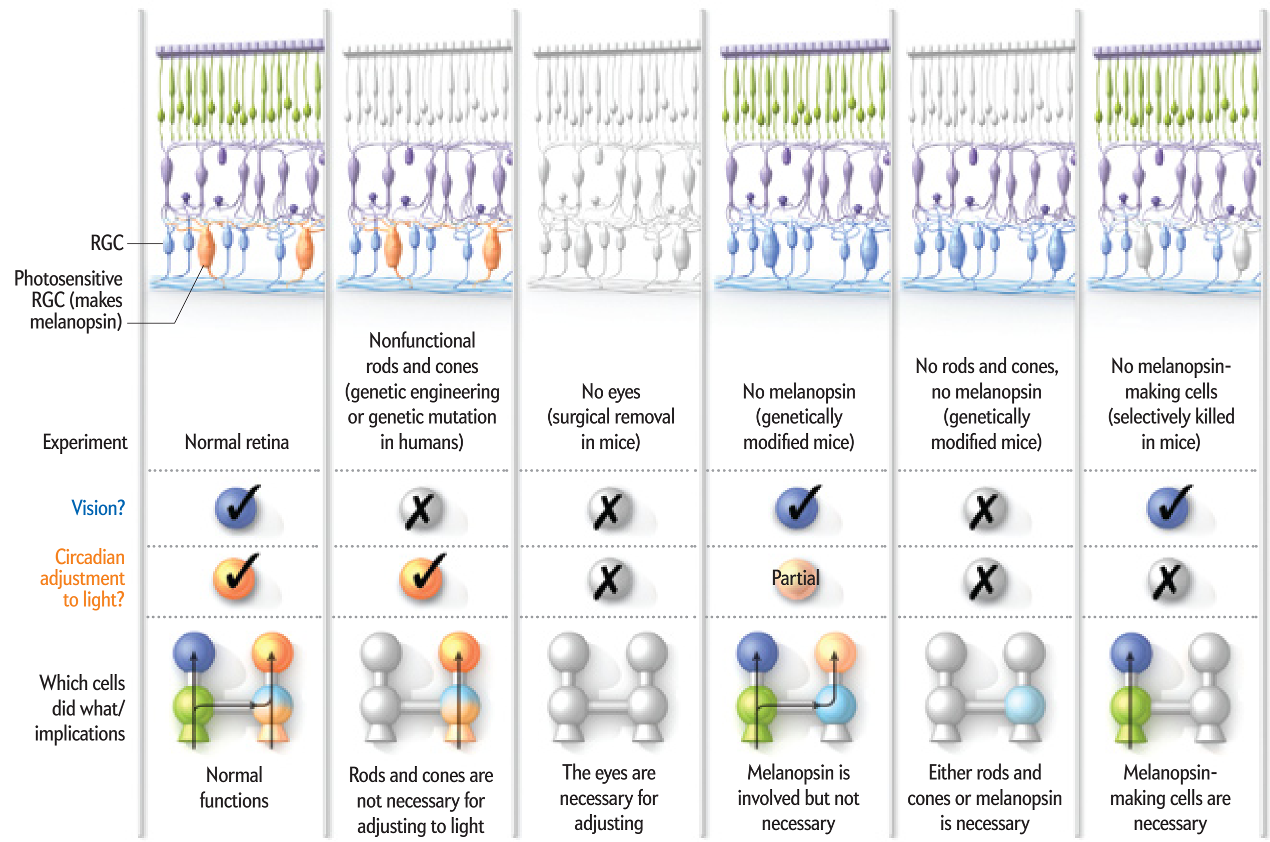


Illustration by Bryan Christie

dark cycle. But eyeless mice, which lacked retinas altogether, would lose those abilities.

One additional test was left to seal the case. I and others thought that if we bred mice that were normal except for lacking the gene for melanopsin, the mice, being unable to produce the pigment, would have no nonvisual responses to light. What happened next confirmed a favorite mantra in our laboratory: "Science is a cruel mistress." Just when we thought we were about to nail down the answer to our mystery, we were absolutely dumbfounded to find that the melanopsin-free mice had little trouble adjusting their circadian clocks.

ONE LAST HURDLE

TO EXPLAIN THIS SETBACK, we considered the possibility that perhaps yet another nonvisual photoreceptor could be lurking in the retina. But this possibility seemed unlikely for a variety of reasons. Most significant, the complete mouse genome, which was sequenced around the time we completed the studies on our knockout mice, contained no other obvious photopigment genes.

The second hypothesis was that perhaps rods, cones and photosensitive ganglion cells acted together to control nonvisual responses to light. This last possibility was put to the test when we engineered mice that completely lacked rods, cones and melanopsin. These "frankenmice" failed to show any visual or nonvisual responses to light and behaved as though their eyes had been surgically removed. Finally, we were able to conclude that rods, cones and the melanopsin-containing ganglion cells all work together to bring nonvisual light information to the brain.

In fact, evidence is emerging that photosensitive ganglion cells also function as a conduit for transmitting nonvisual light information from the rods and cones to the brain, just like the other retinal ganglion cells transmit visual information to the visual areas of the brain. In 2008 three different groups, including ours, each devised a method to kill photosensitive ganglion cells in mice without affecting the rest of the organism. Although the mice retained their vision, they tended to get their days and nights mixed up and also had trouble constricting their pupils [*see box on opposite page*]. In other words, the specialized ganglion cells are necessary to engender nonvisual responses to light, but the system has some built-in redundancy: these cells can either detect light autonomously or relay information from the rods and cones, or both.

So the puzzle was finally solved—at least as far as mice were concerned. But evidence has emerged that the same physiological mechanism may exist in humans, too. Foster and his collaborators published a study in 2007 of two blind patients who lacked functional rods and cones—the human equivalent of Keeler's mice—but who could still adjust their circadian rhythms when periodically exposed to blue light. The wavelengths of blue light where their response was optimal were precisely in the same range that melanopsin can detect—as measured in studies by my group in collaboration with Berson's in which we forced normally nonphotoreceptive cell lines to produce melanopsin. Those cells responded to light by firing in response to blue light.

Perhaps more interesting, we found that when struck by light, melanopsin initiates a chemical signaling cascade inside these cells that more closely resembles what happens in fly and squid photoreceptors than in mammals' rods and cones. Again, this was not completely unexpected, because we had recognized years earlier that the gene sequence for melanopsin more closely resembled the gene sequences of photopigments in invertebrates than those in vertebrates. Thus, in mammals, melanopsin appears to be the photopigment of a previously unknown and primitive nonvisual photoreceptive system, one housed within the retina alongside its more "advanced" cousin, the visual system.

Aside from pure scientific interest, the discovery of this new, hidden "organ" may have clinical implications as well, because it points to a previously unappreciated link between eye health and mental health. Studies suggest that exposure to blue light may increase awareness, counteracting jet lag or sleep deprivation, and alleviate seasonal affective disorder—a common problem at high latitudes that can cause debilitating depression and may induce suicide. It seems natural to assume that light therapy is effective because it targets photosensitive ganglion cells. Other studies have shown that blind children suffering from diseases that affect retinal ganglion cells, such as glaucoma, seem to be at higher risk of suffering from sleep disorders than children who are blind for other reasons. Targeting the health of photosensitive ganglion cells could thus lead to a new class of treatments for a wide variety of conditions. SA

GALLERY

Feeling Light, Not Seeing

Most organisms set their biological rhythms by detecting daylight and dark. Some animals do so with specialized, nonvisual light-sensing organs, which in some cases are used for other nonvisual responses to light as well, such as to help the animal hide. Although in humans and other mammals the nonvisual receptors are in the eyes, some animals have them elsewhere.

Tadpoles (the larvae of frogs) and other amphibians detect light with pigmented cells on their skin so that they can adapt their camouflage to different backgrounds.

Sparrows can adjust their circadian rhythms even when deprived of their eyes. Specialized cells in their brain can sense light through feathers, skin and bone.

Mice were the first mammals found to adjust their circadian rhythms even when blind. They may also retain responses such as constricting and dilating their pupils.

KIM TAYLOR AND JANE BURTON *Getty Images* (*tadpole*); CYRIL LAUBSCHER *Getty Images* (*sparrow*); GETTY IMAGES (*mouse*)

MORE TO EXPLORE

Melanopsin: An Opsin in Melanophores, Brain, and Eye. Ignacio Provencio, Guisen Jiang, Willem J. De Grip, William Pär Hayes and Mark D. Rollag in *Proceedings of the National Academy of Sciences USA,* Vol. 95, No. 1, pages 340–345; January 6, 1998.

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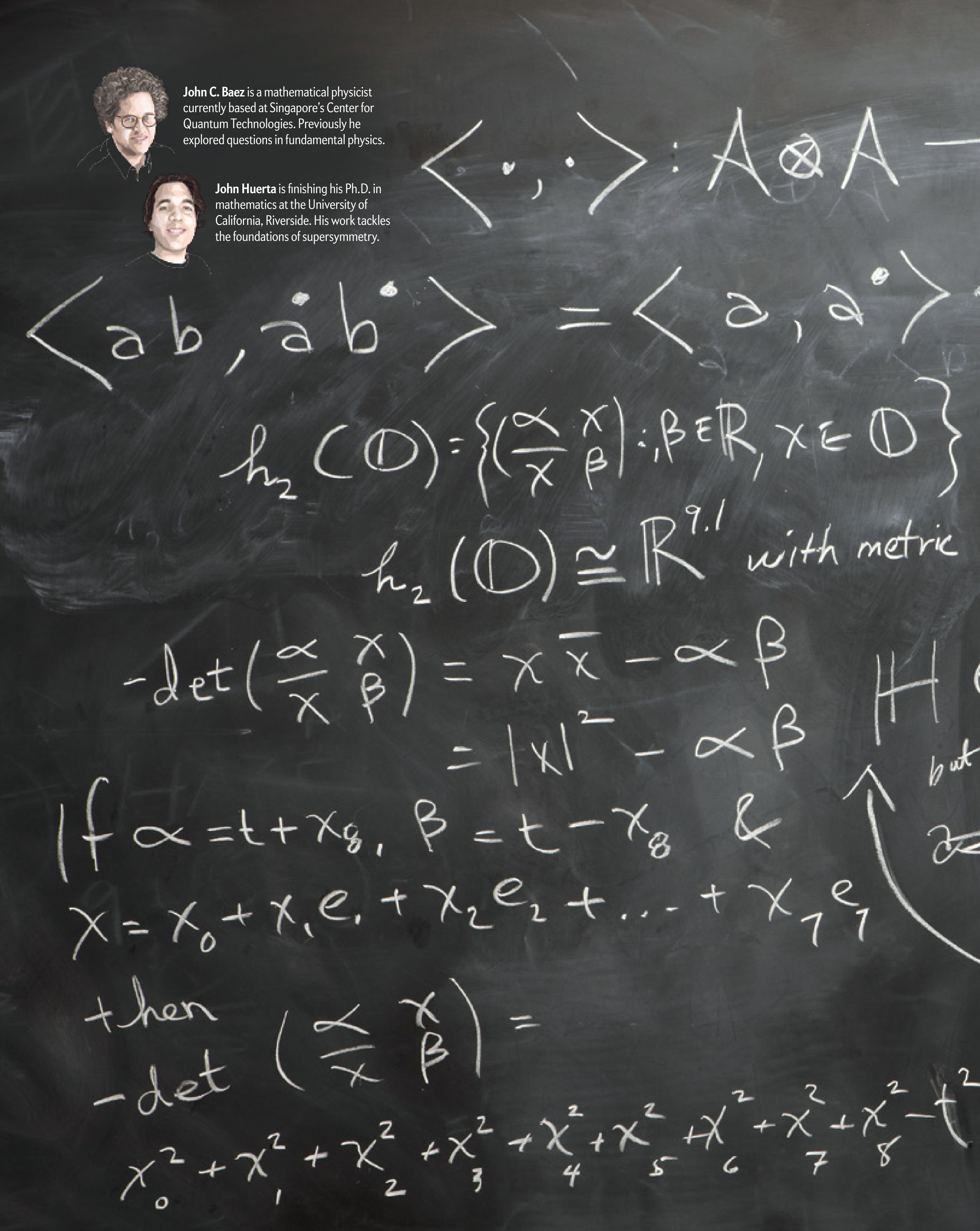
An online guide to the retina: **webvision.med.utah.edu**

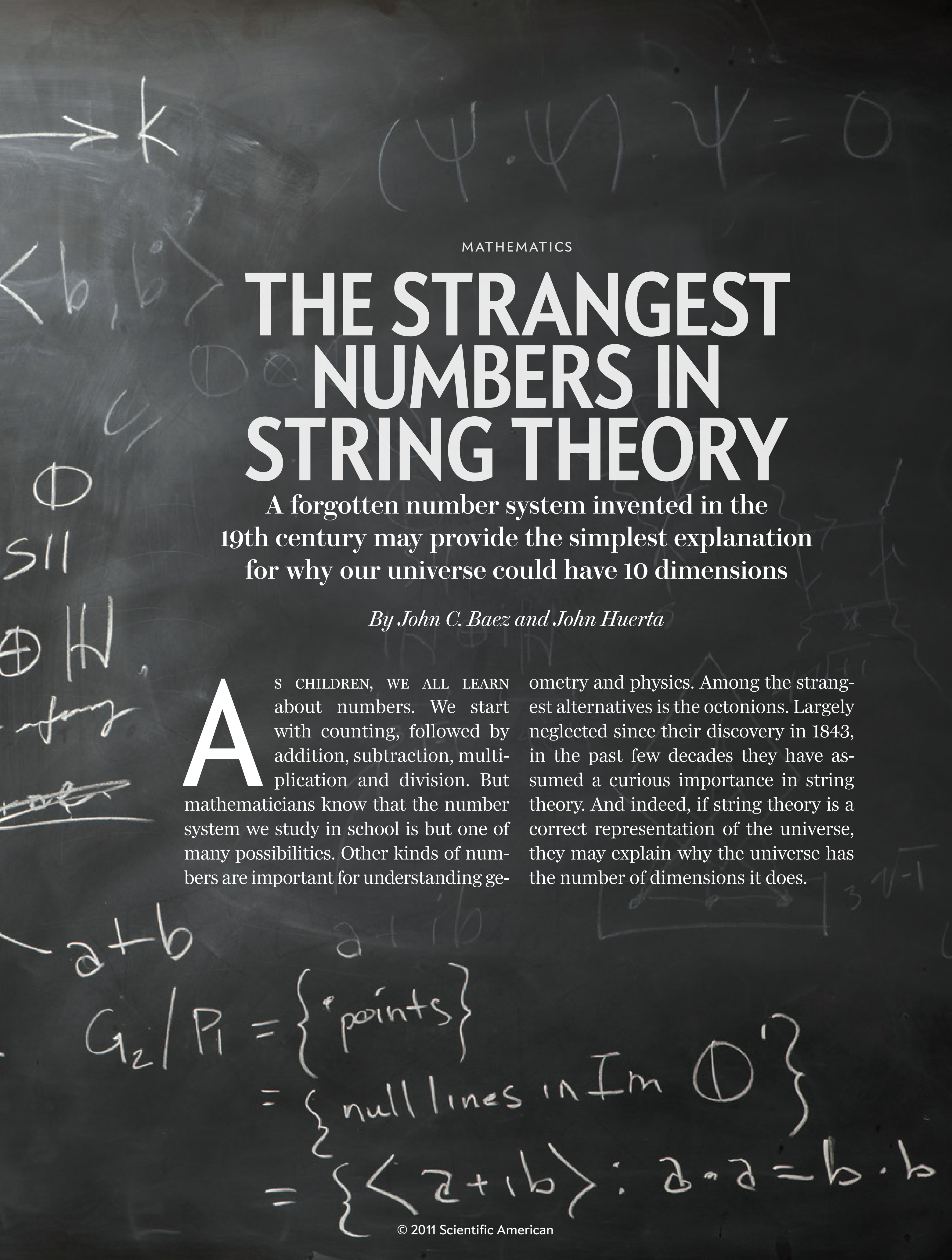
SCIENTIFIC AMERICAN ONLINE
Learn more about circadian disorders and remedies for them at **ScientificAmerican.com/may2011/circadian**

John C. Baez is a mathematical physicist currently based at Singapore's Center for Quantum Technologies. Previously he explored questions in fundamental physics.

John Huerta is finishing his Ph.D. in mathematics at the University of California, Riverside. His work tackles the foundations of supersymmetry.



Photographs by Zachary Zavislak



MATHEMATICS

THE STRANGEST NUMBERS IN STRING THEORY

A forgotten number system invented in the 19th century may provide the simplest explanation for why our universe could have 10 dimensions

By John C. Baez and John Huerta

As children, we all learn about numbers. We start with counting, followed by addition, subtraction, multiplication and division. But mathematicians know that the number system we study in school is but one of many possibilities. Other kinds of numbers are important for understanding geometry and physics. Among the strangest alternatives is the octonions. Largely neglected since their discovery in 1843, in the past few decades they have assumed a curious importance in string theory. And indeed, if string theory is a correct representation of the universe, they may explain why the universe has the number of dimensions it does.

THE IMAGINARY MADE REAL

THE OCTONIONS WOULD NOT BE the first piece of pure mathematics that was later used to enhance our understanding of the cosmos. Nor would it be the first alternative number system that was later shown to have practical uses. To understand why, we first have to look at the simplest case of numbers—the number system we learned about in school—which mathematicians call the real numbers. The set of all real numbers forms a line, so we say that the collection of real numbers is one-dimensional. We could also turn this idea on its head: the line is one-dimensional because specifying a point on it requires one real number.

Before the 1500s the real numbers were the only game in town. Then, during the Renaissance, ambitious mathematicians attempted to solve ever more complex forms of equations, even holding competitions to see who could solve the most difficult problems. The square root of –1 was introduced as a kind of secret weapon by Italian mathematician, physician, gambler and astrologer Gerolamo Cardano. Where others might cavil, he boldly let himself use this mysterious number as part of longer calculations where the answers were ordinary real numbers. He was not sure why this trick worked; all he knew was that it gave him the right answers. He published his ideas in 1545, thus beginning a controversy that lasted for centuries: Does the square root of –1 really exist, or is it only a trick? Nearly 100 years later no less a thinker than René Descartes rendered his verdict when he gave it the derogatory name "imaginary," now abbreviated as i.

Nevertheless, mathematicians followed in Cardano's footsteps and began working with complex numbers—numbers of the form $a + bi$, where a and b are ordinary real numbers. Around 1806 Jean-Robert Argand popularized the idea that complex numbers describe points on the plane. How does $a + bi$ describe a point on the plane? Simple: the number a tells us how far left or right the point is, whereas b tells us how far up or down it is.

In this way, we can think of any complex number as a point in the plane, but Argand went a step further: he showed how to think of the operations one can do with complex numbers—addition, subtraction, multiplication and division—as geometric manipulations in the plane [*see lower box on opposite page*].

As a warm-up for understanding how these operations can be thought of as geometric manipulations, first think about the real numbers. Adding or subtracting any real number slides the real line to the right or left. Multiplying or dividing by any positive number stretches or squashes the line. For example, multiplying by 2 stretches the line by a factor of 2, whereas dividing by 2 squashes it down, moving all the points twice as close as they were. Multiplying by –1 flips the line over.

If string theory is right, the octonions provide the deep reason why the universe must have 10 dimensions.

The same procedure works for complex numbers, with just a few extra twists. Adding any complex number $a + bi$ to a point in the plane slides that point right (or left) by an amount a and up (or down) by an amount b. Multiplying by a complex number stretches or squashes but also *rotates* the complex plane. In particular, multiplying by i rotates the plane a quarter turn. Thus, if we multiply 1 by i twice, we rotate the plane a full half-turn from the starting point to arrive at –1. Division is the opposite of multiplication, so to divide we just shrink instead of stretching, or vice versa, and then rotate in the opposite direction.

Almost everything we can do with real numbers can also be done with complex numbers. In fact, most things work better, as Cardano knew, because we can solve more equations with complex numbers than with real numbers. But if a two-dimensional number system gives the user added calculating power, what about even higher-dimensional systems? Unfortunately, a simple extension turns out to be impossible. An Irish mathematician would uncover the secret to higher-dimensional number systems decades later. And only now, two centuries on, are we beginning to understand how powerful they can be.

HAMILTON'S ALCHEMY

IN 1835, at the age of 30, mathematician and physicist William Rowan Hamilton discovered how to treat complex numbers as pairs of real numbers. At the time mathematicians commonly wrote complex numbers in the form $a + bi$ that Argand popularized, but Hamilton noted that we are also free to think of the number $a + bi$ as just a peculiar way of writing two real numbers—for instance (a, b).

This notation makes it very easy to add and subtract complex numbers—just add or subtract the corresponding real numbers in the pair. Hamilton also came up with slightly more involved rules for how to multiply and divide complex numbers so that they maintained the nice geometric meaning discovered by Argand.

After Hamilton invented this algebraic system for complex numbers that had a geometric meaning, he tried for many years to invent a bigger algebra of triplets that would play a similar role in three-dimensional geometry, an effort that gave him no end of frustrations. He once wrote to his son, "Every morning … on my coming down to breakfast, your (then) little brother William Edwin, and yourself, used to ask me: 'Well, Papa, can you multiply triplets?' Whereto I was always obliged to reply, with a sad shake of the head: 'No, I can only add and subtract them.'" Although he could not have known it at the

IN BRIEF

Most everyone is familiar with the "real" numbers, but far more types of numbers exist. Among them, the best known are the complex numbers, which include a square root of –1.

We can build higher-dimensional number systems as well. But we can define all the four basic operations—addition, subtraction, multiplication and division—in only a few special cases.

One such case is the octonions, an eight-dimensional number system. Mathematicians invented it in the 1840s but, finding few applications, paid little attention for the next 150-plus years.

Mathematicians now suspect that the octonions may help us understand advanced research in particle physics in fields such as supersymmetry and string theory.

time, the task he had given himself was mathematically impossible.

Hamilton was searching for a three-dimensional number system in which he could add, subtract, multiply and divide. Division is the hard part: a number system where we can divide is called a division algebra. Not until 1958 did three mathematicians prove an amazing fact that had been suspected for decades: any division algebra must have dimension one (which is just the real numbers), two (the complex numbers), four or eight. To succeed, Hamilton had to change the rules of the game.

Hamilton himself figured out a solution on October 16, 1843. He was walking with his wife along the Royal Canal to a meeting of the Royal Irish Academy in Dublin when he had a sudden revelation. In three dimensions, rotations, stretching and shrinking could not be described with just three numbers. He needed a fourth number, thereby generating a four-dimensional set called quaternions that take the form $a + bi + cj + dk$. Here the numbers i, j and k are three different square roots of –1.

Hamilton would later write: "I then and there felt the galvanic circuit of thought close; and the sparks which fell from it were the fundamental equations between i, j and k; exactly such as I have used them ever since." And in a noteworthy act of mathematical vandalism, he carved these equations into the stone of the Brougham Bridge. Although they are now buried under graffiti, a plaque has been placed there to commemorate the discovery.

It may seem odd that we need points in a four-dimensional space to describe changes in three-dimensional space, but it is true. Three of the numbers come from describing rotations, which we can see most readily if we imagine trying to fly an airplane. To orient the plane, we need to control the pitch, or angle with the horizontal. We also may need to adjust the yaw, by turning left or right, as a car does. And finally, we may need to adjust the roll: the angle of the plane's wings. The fourth number we need is used to describe stretching or shrinking.

Hamilton spent the rest of his life obsessed with the quaternions and found many practical uses for them. Today in many of these applications the quaternions have been replaced by their simpler cousins: vectors, which can be thought of

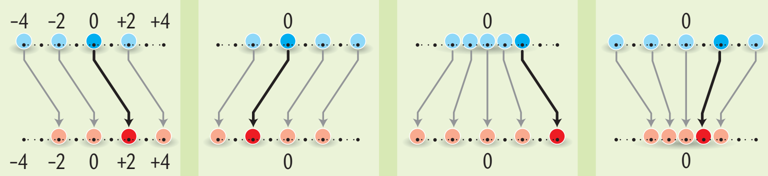
BEYOND THE REAL LINE

Math in Multiple Dimensions

In grade school we are taught to connect the abstract ideas of addition and subtraction to concrete operations—moving numbers up and down the number line. This connection between algebra and geometry turns out to be incredibly powerful. Because of it, mathematicians can use the algebra of the octonions to solve problems in hard-to-imagine eight-dimensional worlds. The panels below show how to extend algebraic operations on the real-number line to complex (two-dimensional) numbers.

Real Numbers

Addition $0 + 2 = 2$ | **Subtraction** $0 - 2 = -2$ | **Multiplication** $2 \times 2 = 4$ | **Division** $2 \div 2 = 1$



Addition along the real-number line is simple: just shift each number to the right by the amount you are adding.

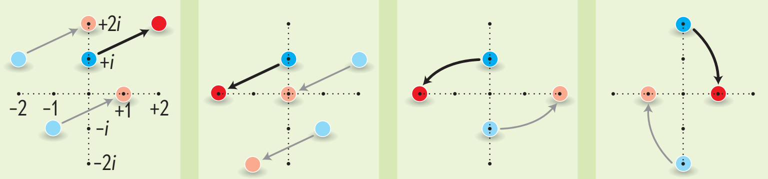
Subtraction operates the same way, but here we shift numbers to the left.

In multiplication, we stretch the number line out by a constant factor.

Division is equivalent to shrinking the points on the number line.

Complex Numbers

Addition $i + (2 + i) = 2 + 2i$ | **Subtraction** $i - (2 + i) = -2 + 0i$ | **Multiplication** $i \times (2i) = -2$ | **Division** $2i \div (2i) = 1$



Complex numbers have two components—the real part, which is measured on the horizontal axis, and the imaginary part (noted by the i), which goes up the vertical axis. Adding two complex numbers shifts the original number to the *right* by the amount in the real part and *up* by the amount in the imaginary part.

Similarly, when we subtract complex numbers we shift the original point to the *left* by the amount in the real part and *down* by the amount in the imaginary part.

Multiplication is where the fun begins: Just as in the case of the real numbers, multiplication stretches a complex number. Moreover, multiplication by i rotates the point counterclockwise by 90 degrees.

Division shrinks a complex number, just as in the case of the real numbers. Division by i also rotates a complex number clockwise by 90 degrees.

Illustrations by Brown Bird Design

as quaternions of the special form $ai + bj + ck$ (the first number is just zero). Yet quaternions still have their niche: they provide an efficient way to represent three-dimensional rotations on a computer and show up wherever this is needed, from the attitude-control system of a spacecraft to the graphics engine of a video game.

IMAGINARIES WITHOUT END

DESPITE THESE APPLICATIONS, we might wonder what, exactly, are j and k if we have already defined the square root of –1 as i. Do these square roots of –1 really exist? Can we just keep inventing new square roots of –1 to our heart's content?

These questions were asked by Hamilton's college friend, a lawyer named John Graves, whose amateur interest in algebra got Hamilton thinking about complex numbers and triplets in the first place. The very day after his fateful walk in the fall of 1843, Hamilton sent Graves a letter describing his breakthrough. Graves replied nine days later, complimenting Hamilton on the boldness of the idea but adding, "There is still something in the system which gravels me. I have not yet any clear views as to the extent to which we are at liberty arbitrarily to create imaginaries, and to endow them with supernatural properties." And he asked: "If with your alchemy you can make three pounds of gold, why should you stop there?"

Like Cardano before him, Graves set his concerns aside for long enough to conjure some gold of his own. On December 26 he wrote again to Hamilton, describing a new eight-dimensional number system that he called the octaves and that are now called octonions. Graves was unable to get Hamilton interested in his ideas, however. Hamilton promised to speak about Graves's octaves at the Irish Royal Society, which is one way mathematical results were published at the time. But Hamilton kept putting it off, and in 1845 the young genius Arthur Cayley rediscovered the octonions and beat Graves to publication. For this reason, the octonions are also sometimes known as Cayley numbers.

Why didn't Hamilton like the octonions? For one thing, he was obsessed with research on his own discovery, the quaternions. He also had a purely mathematical reason: the octonions break some cherished laws of arithmetic.

The quaternions were already a bit strange. When you multiply real numbers, it does not matter in which order you do it—2 times 3 equals 3 times 2, for example. We say that multiplication commutes. The same holds for complex numbers. But quaternions are noncommutative. The order of multiplication matters.

Order is important because quaternions describe rotations in three dimensions, and for such rotations the order makes a difference to the outcome. You can check this out yourself [*see box below*]. Take a book, flip it top to bottom (so that you are now viewing the back cover) and give it a quarter turn clockwise (as viewed from above). Now do these two operations in reverse order: first rotate a quarter turn, then flip. The final position has changed. Because the result depends on the order, rotations do not commute.

The octonions are much stranger. Not only are they noncommutative, they also break another familiar law of arithmetic: the associative law $(xy)z = x(yz)$. We have all seen a nonassociative operation in our study of mathematics: subtraction. For example, $(3 - 2) - 1$ is different from $3 - (2 - 1)$. But we are used to multiplication being associative, and most mathematicians still feel this way, even though they have gotten used to noncommutative operations. Rotations are associative, for example, even though they do not commute.

But perhaps most important, it was not clear in Hamilton's time just what the octonions would be good for. They are closely related to the geometry of seven and eight dimensions, and we can describe rotations in those dimensions using the multiplication of octonions. But for more than a century that was a purely intellectual exercise. It would take the development of modern particle physics—and string theory in particular—to see how the octonions might be useful in the real world.

SYMMETRY AND STRINGS

IN THE 1970s AND 1980s theoretical physicists developed a strikingly beautiful idea called supersymmetry. (Later researchers would learn that string theory requires supersymmetry.) It states that at the most

VISUALIZING 4-D

The Problem with Rotations

Ordinarily you can multiply numbers together in whatever order you like. For example, 2 times 3 is the same as 3 times 2. In higher-dimensional number systems such as the quaternions and octonions, however, order is very important. Consider the quaternions, which describe rotations in three dimensions. If we take an object such as a book, the order in which we rotate it has a great effect on its final orientation. In the top row at the right, we flip the book vertically, then rotate it, revealing the page edges. In the bottom row, rotating the book and then flipping reveal the spine on the opposite side.

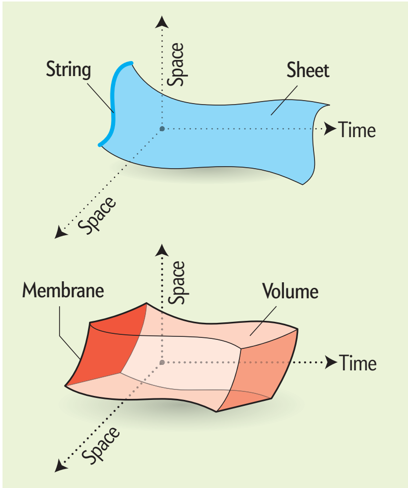
fundamental levels, the universe exhibits a symmetry between matter and the forces of nature. Every matter particle (such as an electron) has a partner particle that carries a force. And every force particle (such as a photon, the carrier of the electromagnetic force) has a twin matter particle.

Supersymmetry also encompasses the idea that the laws of physics would remain unchanged if we exchanged all the matter and force particles. Imagine viewing the universe in a strange mirror that, rather than interchanging left and right, traded every force particle for a matter particle, and vice versa. If supersymmetry is true, if it truly describes our universe, this mirror universe would act the same as ours. Even though physicists have not yet found any concrete experimental evidence in support of supersymmetry, the theory is so seductively beautiful and has led to so much enchanting mathematics that many physicists hope and expect that it is real.

One thing we know to be true, however, is quantum mechanics. And according to quantum mechanics, particles are also waves. In the standard three-dimensional version of quantum mechanics that physicists use every day, one type of number (called spinors) describes the wave motion of matter particles. Another type of number (called vectors) describes the wave motion of force particles. If we want to understand particle interactions, we have to combine these two using a cobbled-together simulacrum of multiplication. Although the system we use right now might work, it is not very elegant at all.

As an alternative, imagine a strange universe with no time, only space. If this universe has dimension one, two, four or eight, both matter and force particles would be waves described by a single type of number—namely, a number in a division algebra, the only type of system that allows for addition, subtraction, multiplication and division. In other words, in these dimensions the vectors and spinors coincide: they are each just real numbers, complex numbers, quaternions or octonions, respectively. Supersymmetry emerges naturally, providing a unified description of matter and forces. Simple multiplication describes interactions, and all particles—no matter the type—use the same number system.

Yet our plaything universe cannot be real, because we need to take time into account. In string theory, this consideration has an intriguing effect. At any moment



In string theory, one-dimensional strings trace out two-dimensional surfaces over time. In M-theory, two-dimensional membranes trace out three-dimensional volumes. Adding these dimensions to the eight dimensions of the octonions provides clues as to why these theories require 10 or 11 dimensions.

in time a string is a one-dimensional thing, like a curve or line. But this string traces out a two-dimensional surface as time passes [*see illustration above*]. This evolution changes the dimensions in which supersymmetry arises, by adding two—one for the string and one for time. Instead of supersymmetry in dimension one, two, four or eight, we get supersymmetry in dimension three, four, six or 10.

Coincidentally string theorists have for years been saying that only 10-dimensional versions of the theory are self-consistent. The rest suffer from glitches called anomalies, where computing the same thing in two different ways gives different answers. In anything other than 10 dimensions, string theory breaks down. But 10-dimensional string theory is, as we have just seen, the version of the theory that uses octonions. So if string theory is right, the octonions are not a useless curiosity: on the contrary, they provide the deep reason why the universe must have 10 dimensions: in 10 dimensions, matter and force particles are embodied in the same type of numbers—the octonions.

But this is not the end of the story. Recently physicists have started to go beyond strings to consider membranes. For example, a two-dimensional membrane, or 2-brane, looks like a sheet at any instant. As time passes, it traces out a three-dimensional volume in spacetime.

Whereas in string theory we had to add two dimensions to our standard collection of one, two, four and eight, now we must add three. Thus, when we are dealing with membranes we would expect supersymmetry to naturally emerge in dimensions four, five, seven and 11. And as in string theory we have a surprise in store: researchers tell us that M-theory (the "M" typically stands for "membrane") requires 11 dimensions—implying that it should naturally make use of octonions. Alas, nobody understands M-theory well enough to even write down its basic equations (that M can also stand for "mysterious"). It is hard to tell precisely what shape it might take in the future.

At this point we should emphasize that string theory and M-theory have as of yet made no experimentally testable predictions. They are beautiful dreams—but so far only dreams. The universe we live in does not look 10- or 11-dimensional, and we have not seen any symmetry between matter and force particles. David Gross, one of the world's leading experts on string theory, currently puts the odds of seeing some evidence for supersymmetry at CERN's Large Hadron Collider at 50 percent. Skeptics say they are much less. Only time will tell.

Because of this uncertainty, we are still a long way from knowing if the strange octonions are of fundamental importance in understanding the world we see around us or merely a piece of beautiful mathematics. Of course, mathematical beauty is a worthy end in itself, but it would be even more delightful if the octonions turned out to be built into the fabric of nature. As the story of the complex numbers and countless other mathematical developments demonstrates, it would hardly be the first time that purely mathematical inventions later provided precisely the tools that physicists need. SA

MORE TO EXPLORE

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Ubiquitous Octonions. Helen Joyce in *Plus Magazine,* Vol. 33; January 2005. **http://plus.maths.org/content/33**

SCIENTIFIC AMERICAN ONLINE
Watch three-dimensional rotations in action at **ScientificAmerican.com/may2011/octonions**

MEDICINE

Fast Track to Vaccines

Analyzing all the layers of the immune system at once speeds design and may one day deal a decisive blow against HIV

By Alan Aderem

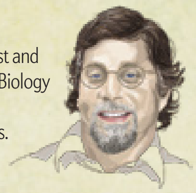
AIDS RESEARCHERS AND ADVOCATES WERE devastated in 2007, when a much anticipated vaccine against HIV unexpectedly failed to protect anyone in a clinical trial of 3,000 people. Even worse, the experimental inoculation, developed with money from the Merck pharmaceutical company and the National Institute of Allergy and Infectious Diseases, actually increased the chances that some people would later acquire HIV. Millions of dollars and more than a decade of research had gone into creating the vaccine. Meanwhile, in that same 10-year period, 18 million people died of AIDS, and millions more were infected.

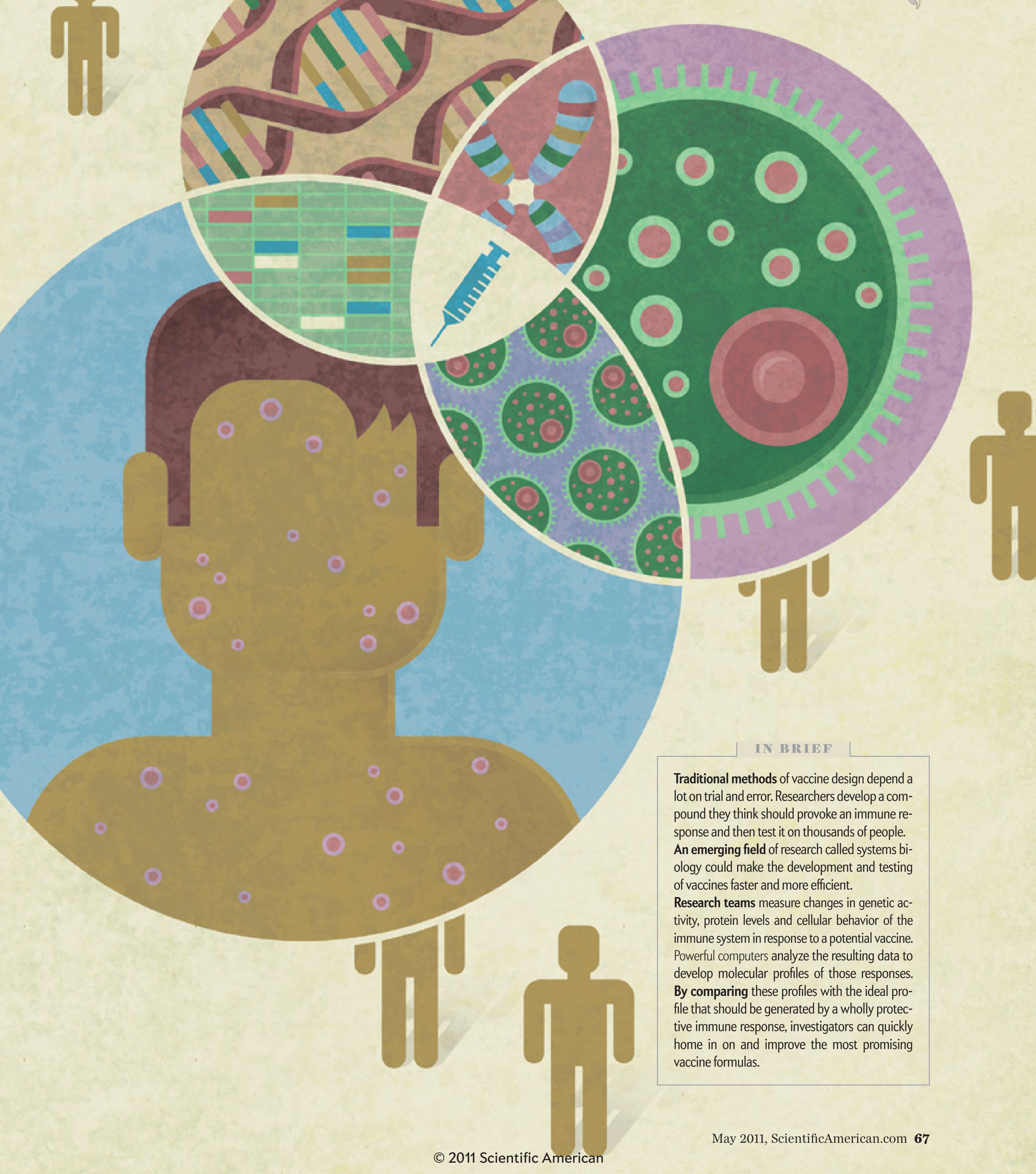
The Merck vaccine failed in large part because investigators do not yet know how to create the perfect vaccine. Yes, a number of vaccines have been spectacularly successful. Think of polio and smallpox. In truth, though, luck played a big role in those successes. Based on limited knowledge of the immune system and of the biology of a pathogen, investigators made educated guesses at vaccine formulations that might work and then, perhaps after some tinkering, had the good fortune to be proved right when the vaccine protected people. But all too often lack of insight into the needed immune response leads to disappointment, with a vaccine candidate recognized as ineffective only after a large human trial has been performed.

What if investigators had a way to develop and evaluate potential vaccines that was faster and more efficient? Ideally, the alternative method would include a clear understanding of the precise mixture of immunological responses that must occur if a vaccine is to induce a strong protective reaction. Which subset of immune cells needs to interact with one another, for instance, and in what ways? Which collection of genes must those cells activate or depress? Researchers could then assemble such informa-

Illustrations by Jude Buffum

Alan Aderem is an internationally known immunologist and cell biologist who co-founded the Institute for Systems Biology in Seattle in 2000. He is now director of Seattle BioMed, an institute that focuses on the development of vaccines.





IN BRIEF

Traditional methods of vaccine design depend a lot on trial and error. Researchers develop a compound they think should provoke an immune response and then test it on thousands of people.

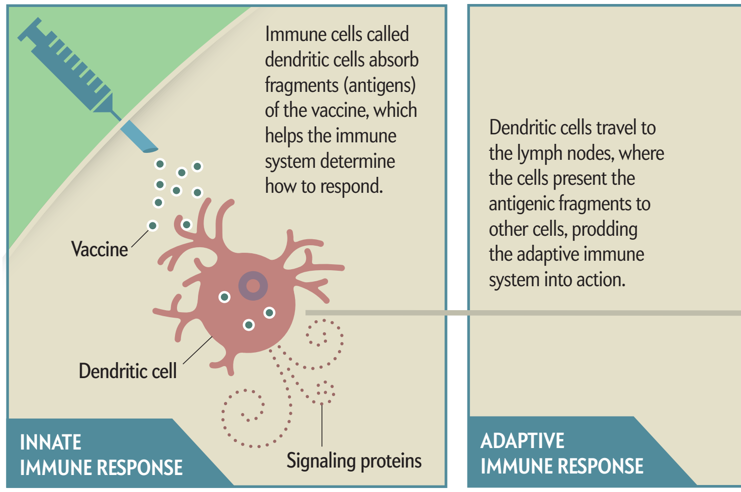
An emerging field of research called systems biology could make the development and testing of vaccines faster and more efficient.

Research teams measure changes in genetic activity, protein levels and cellular behavior of the immune system in response to a potential vaccine. Powerful computers analyze the resulting data to develop molecular profiles of those responses.

By comparing these profiles with the ideal profile that should be generated by a wholly protective immune response, investigators can quickly home in on and improve the most promising vaccine formulas.

Defense in Depth

To be successful, a vaccine must train the immune system to mount a vigorous defense against a particular virus, bacterium or other pathogen before infection with the disease-causing agent occurs. The best vaccine preparations (for example, whole or inactivated viruses or pieces of viruses) evoke multiple sequential reactions from two branches of the immune system: the innate and the adaptive immune systems. This diagram highlights major steps in the complex ballet of battlefield preparations. A subset of the body's frontline defenders, the dendritic cells, are generalists that respond soon after inoculation occurs. They engulf the vaccine and then hand off the mission to specialists—the T cells and antibody-producing B cells—to remember the invader and prime the body to repel future attacks from the same or similar microbial enemies.



tion into a system-wide profile or signature of protective immunity. This pattern, in turn, could serve as a guide for determining exactly what a vaccine needs to do to prevent disease. Scientists could compare hundreds of possible formulas, choosing to pursue only the ones that give rise to an immunological profile that is close to ideal. Then they could work on improving those potential vaccine formulas in small, quick human trials until they finally develop a handful of candidates that generate biological signatures as near to optimal as possible. By trying to match the ideal signature in these small tests, they could learn in a remarkably short period whether a vaccine had a good chance of working. By the time the final experimental vaccine was tested in large clinical trials on people, it would be virtually guaranteed to succeed.

Until recently, scientists did not have the tools or the expertise to come close to that vision. We needed interdisciplinary teams able, collectively, to understand immunology and microbial biology, as well as how to model complex biological systems and find useful patterns in vast amounts of data. And we needed technologies able to simultaneously and repeatedly measure changes in gene activity, protein levels, cellular behavior and other features of immune responses—not to mention the computers and software able to process all those data.

Now, however, a number of investigators who work in a field called systems biology are assembling such teams and have taken the first steps toward developing tools that could greatly improve the way vaccines are designed. As a community, we are beginning to decipher in detail the immune responses needed to protect a person against HIV. Systems biology approaches are now being used to develop vaccines against AIDS, as well as tuberculosis, malaria and influenza.

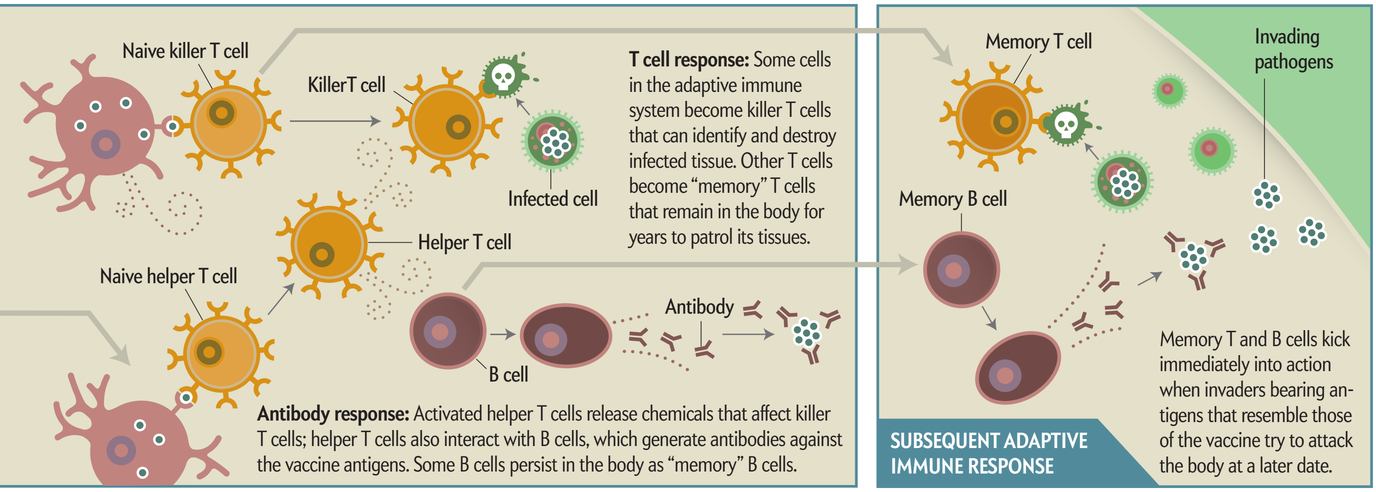
TEST CASE

ALL VACCINES, whether formulated in the classic way or based on systems biology research, contain bits and pieces of viruses, bacteria or parasites that trigger very specific immune responses. Sometimes these bits and pieces, which scientists call antigens, are part of a whole but weaker virus (as was the case 200 years ago, when Edward Jenner inoculated a young boy against smallpox with the pus from a milkmaid's cowpox blister). Other times the antigens are part of a whole but completely inactivated form of an infectious agent (such as the Salk version of the polio vaccine), or the antigen particles serve as the vaccine all by themselves (as in the vaccines against diphtheria, pertussis and tetanus). Vaccines may also include adjuvants—substances that pump up immune activity more generally. When all goes well, the immune system responds to the antigens in a vaccine with a carefully orchestrated cascade of molecular and cellular events that enables the body to block future infection by any virus or bacterium bearing the same or similar antigens. The trick for vaccine developers is to find the right combination of antigenic material and adjuvants to afford the strongest protection.

Despite having been developed in the conventional way, the vaccine against yellow fever, known as YF-17D, hit the nail on the head. It is one of the most effective vaccines ever produced. A single shot provides effective immunity within a week, and protection lasts at least 30 years. This success provided an opportunity to test some of the ideas and methods of systems biology and prompted a study to do just that—which was led by Bali Pulendran of Emory University, with help from Rafi Ahmed's team, also at Emory, and from my group at the Institute for Systems Biology in Seattle (ISB). Because we knew the vaccine worked, we thought we should be able identify a detailed profile of the molecular and cellular changes that account for the success in vaccinated individuals. We did find such a signature and are building on the experience to try to figure out why HIV vaccines have not been able to evoke the immunity needed to prevent infection.

We started our yellow fever experiment by vaccinating 25 healthy volunteers with YF-17D. Then we took blood samples from the subjects at several points: at the time of injection, as well as one, three, seven and 21 days later. Each blood sample was placed into an automated screening device to figure out which genes were being activated. Of course, genes do not directly make the proteins that a cell needs. First the gene's DNA is transcribed into messenger RNA molecules, which in turn are used as templates for building proteins. By looking at the RNA levels, then, we could tell not only which genes were expressed (used to make protein) but also how active they were.

As we expected, the YF-17D inoculation first activated the innate immune system, which is the older (from an evolutionary perspective) of the two branches of the body's defenses. The in-



nate immune system provides an immediate counterattack against all forms of pathogens. Innate immune cells internalize and kill most invading microorganisms. Even though the innate response often takes care of the external threat on its own, the innate immune system instructs the younger adaptive immune system to generate customized responses specifically tailored to the invading pathogen so that the next time the infection occurs, the damage is limited and can be contained more quickly.

About 10 days after inoculation, the innate defenses of our volunteers stimulated the adaptive immune system to react with two sequential salvos. First it generated specialized proteins called antibodies against various parts of the yellow fever virus, and then it activated a group of immune cells called killer T cells that recognize and destroy infected cells in the body. Over the course of several analyses, we identified 65 genes that played key roles in the body's response to the YF-17D vaccine. Closer analysis showed that one specific expression pattern involving those genes was particularly indicative of both powerful antibody and killer T cell activation. In other words, we had proved our point. We could measure in minute detail exactly which genes of the immune system are turned on or off during the course of a robust immune response to the yellow fever vaccine. Rafick-Pierre Sékaly of the Vaccine and Gene Therapy Institute–Florida independently found similar results, and the agreement between the studies was reassuring.

What is especially gratifying about these results is that the signatures of protection, arising from local immune responses at the site of vaccination, can be measured in the bloodstream. In principle, the findings mean that one could develop a simple diagnostic test based on blood from a finger prick to see how well a vaccine is working. Very little advanced training or complex equipment would be needed to collect and analyze data in a field study of a future vaccine—an important point when you consider that HIV, malaria and TB often strike hardest in the poorest parts of the world.

TACKLING HIV/AIDS

HAVING DEMONSTRATED that the systems biology approach could provide a detailed picture of a successful vaccine's effect on the immune system, my colleagues and I joined together to tackle the problem of HIV. Our next best step would have been to compare several vaccine formulas against one another to see if any evoked an ideal immune response. But we did not—and still do not—really know what an ideal immune response to HIV looks like, so finding such a signature is one of our major goals at the moment. We are beginning by looking for clues in animals.

Research has shown that monkeys can be infected with a simian immunodeficiency virus (SIV) that bears many similarities to HIV. This susceptibility is important because monkeys can be deliberately infected in studies, whereas it is unethical to do so to humans.

In collaboration with Louis Picker of Oregon Health and Science University and Robert Seder of the National Institutes of Health, researchers at Seattle BioMed are now testing different SIV-based vaccines in monkeys to learn more about the immunological profile associated with a strong immune response to that virus. To date, we have identified several signatures of the early innate immune response that predict which vaccinated animals will have fewer viruses in their blood after they have been subsequently exposed to SIV.

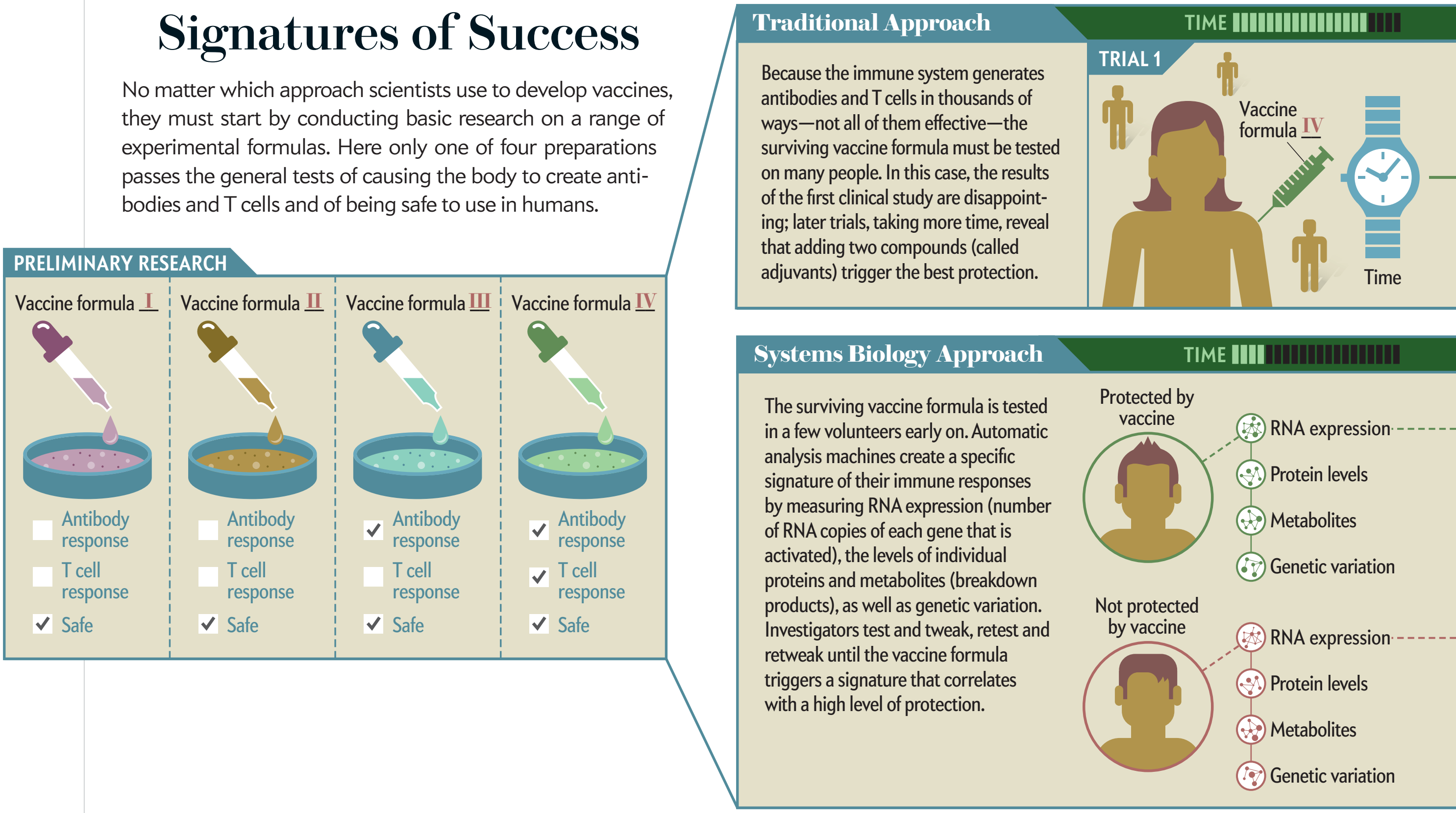
Those genes whose expression correlates with an increased ability to fight off the virus emerge as highly connected nodes in a network diagram of the immune response; the nodes represent individual genes, and the connections between them indicate that they influence one another's activities [*see box on next two pages*]. Because monkeys and people share so many of the same genes, the profile of an optimal monkey response may give us an idea of what the human signature of a strong response to HIV would look like and might also be used to evaluate different vaccines for their ability to work in humans.

Picker and Sékaly are pursuing a related question. They are applying systems-level approaches to learn why vaccines made of weakened versions of SIV are particularly good at protecting nonhuman primates against later infection. Unfortunately in the case of HIV, the use of even a weakened virus is far too dangerous. Over the course of time it could occasionally recombine with full-strength versions of the virus and give people the very illness against which it was meant to protect. (That is why the live form of the polio vaccine is no longer used routinely in the U.S.) Success could point the way to inducing a response akin to

A NEW WAY TO DESIGN VACCINES

Signatures of Success

No matter which approach scientists use to develop vaccines, they must start by conducting basic research on a range of experimental formulas. Here only one of four preparations passes the general tests of causing the body to create antibodies and T cells and of being safe to use in humans.



one provided by a weakened virus without having to take the risk of actually using it in a vaccine.

LEARNING FROM FAILURE

SCIENTISTS from various institutions have now demonstrated that a systems approach can work at multiple stages of vaccine development. We have generated the immune signature of a completely protective vaccine (YF-17D). We have developed immune profiles of successfully vaccinated monkeys. But there are a few more puzzles we hope to solve before trying to develop a new HIV vaccine. Among them: Can we explain exactly why the Merck vaccine failed in 2007—a failure that shocked the AIDS community and that doomed what had seemed like a very promising vaccine candidate?

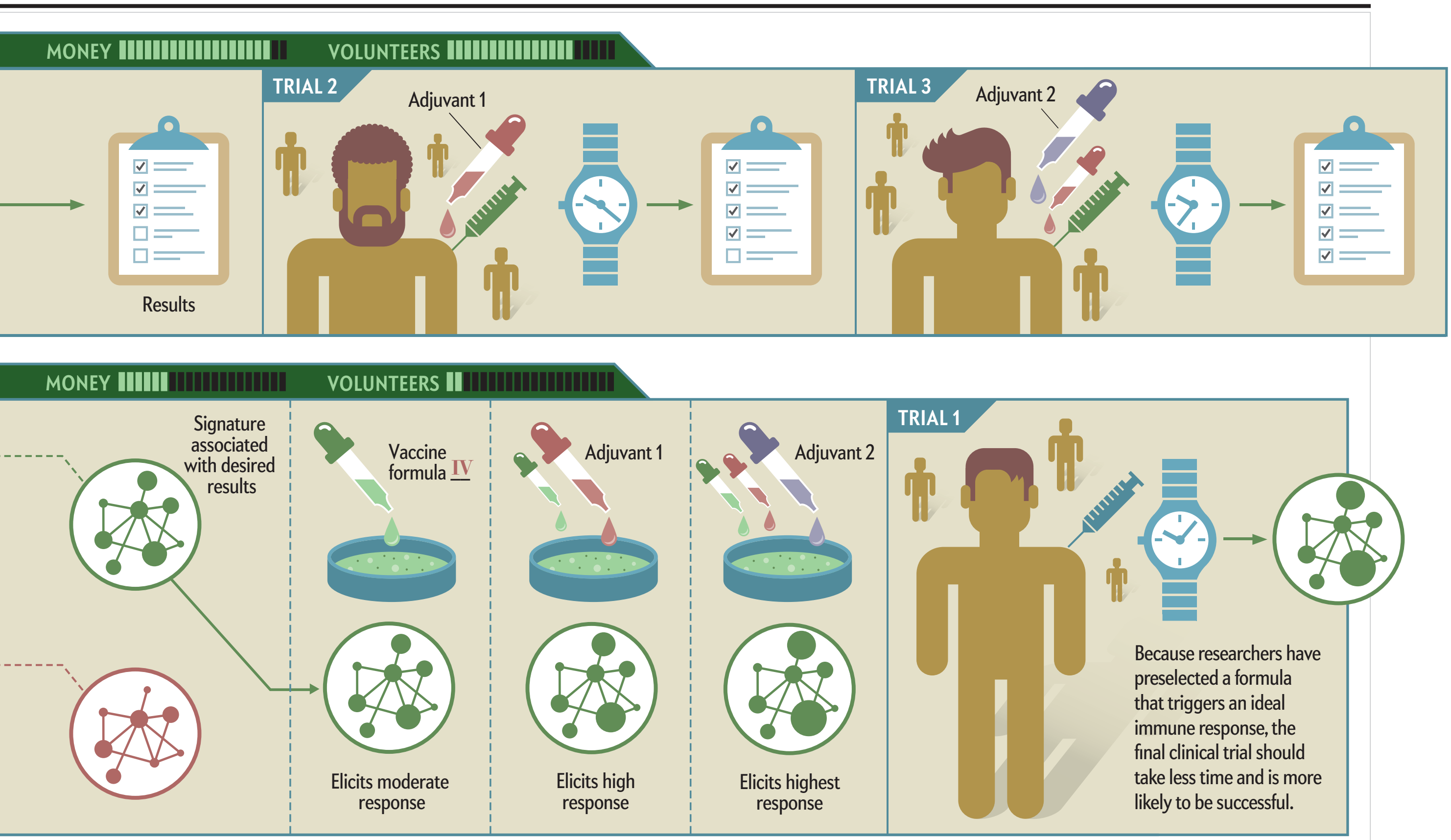
The Merck vaccine (named MRKAd5/HIV-1) was, of course, not the first against HIV to be tested. Previous clinical trials focused on triggering an effective antibody response that would wipe out all HIV particles before they could take hold in the body. Unfortunately, two of the three main strategies for generating such vaccines were unavailable. Using a weakened version of HIV was too dangerous, and completely inactivated HIV particles did not produce the right kinds of antibodies. That left using bits and pieces of HIV either by themselves or attached to other viruses (to pump up immune activity). Alas, even these types of vaccines have not, to date, produced an unequivocally effective antibody response. (The results of a vaccine trial in Thailand, published in 2009, suggested a modestly effective antibody response, but the benefits were not broad enough to protect everyone, and all researchers believe the vaccine needs to be improved.)

The MRKAd5/HIV-1 project took a different tack. Instead of trying to elicit a robust antibody response, it aimed to activate the killer T cell response of the adaptive immune system. As in previous attempts, the Merck vaccine used specific HIV antigens complexed to a safer virus—in this case a type 5 adenovirus, dubbed Ad5—to avoid the problems associated with using a whole HIV particle. (Adenoviruses are a frequent cause of the common cold.) Immunologists understood that the effort—even if completely successful—would not prevent the virus from infecting cells; antibodies also have to be present to achieve that goal. But it would, at least, keep viral reproduction to a minimum, by killing those infected cells. In theory, the vaccine would allow anyone who was exposed to HIV to fight the virus to a standstill indefinitely.

The approach was state of the art. The study would be the first large-scale test of a vaccine specifically designed to activate T cells to kill HIV-infected cells. Pilot studies in nonhuman primates strongly suggested that the vaccine would provide some level of protection in people.

Surprisingly, the Merck vaccine did not work. Despite successfully inducing a T cell response that was precisely directed against HIV-infected cells in more than 75 percent of test subjects (a truly remarkable result), an interim analysis of the data showed that HIV infection rates and viral levels were no different between the vaccine and placebo groups. Even more astonishing, participants with antibodies to Ad5 (because of previous exposure to an unrelated adenovirus type 5 infection) who received the vaccine appeared to be more likely to become infected than those in the placebo group.

We teamed up with Julie McElrath of the Fred Hutchinson



Cancer Research Center in Seattle to analyze the Merck vaccine. Together we determined that exposure to the MRKAd5/HIV-1 vaccine turned on thousands of genes within the first 24 hours after inoculation. That response was consistent with an exceptionally high rate of T cell activation. We further learned that these genes included all the expected major players of the innate immune system. But when we looked at blood samples taken from study subjects who already had antibodies to Ad5 (the same group that exhibited higher HIV infection rates in the vaccine trial), we found that the ramping up of their innate immune system was severely weakened.

Quite possibly that critical weakness—which was completely unanticipated—made those study participants more likely to become infected when they later had sex or shared needles with partners who were HIV-positive. We are currently conducting further studies to see if we can confirm this hypothesis and explain why the strong T cell response did not provide the subjects with any protection.

NEXT STEPS

FOR NOW THE SYSTEMS APPROACH seems best suited to testing experimental vaccines after they have already been formulated to see if they are likely to offer effective protection. Eventually, however, the goal is to design vaccines from beginning to end in such a way that we know in advance that they will trigger the desired immune responses.

Scientists have already made significant progress—for example, in understanding how certain adjuvants affect the immune system. My team has examined the gene networks that are activated by a wide array of adjuvants, and it is clear that some of these adjuvants trigger genes that tend to stimulate T cell responses, whereas other networks are more likely to skew the response toward the production of antibodies. By combining very detailed knowledge about adjuvants with the precise molecular signature of an optimal immune response, it is quite possible we will be able to optimize the production of vaccines against particular pathogens.

In any event, my colleagues and I believe that a systems approach offers the greatest hope for more deliberate and predictable vaccine design. Only by understanding the immune system better can we create effective vaccines for such scourges as AIDS, malaria and tuberculosis. The pathogens that have given rise to these epidemics have so far defeated our utmost efforts at developing vaccines the traditional way. We simply cannot allow another generation of tens of millions of people to be wiped out by these global plagues. SA

MORE TO EXPLORE

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Systems Biology Approach Predicts Immunogenicity of the Yellow Fever Vaccine in Humans. Troy D. Querec et al. in *Nature Immunology,* Vol. 10, No. 1, pages 116–125; January 2009. Published online November 23, 2008. http://www.ncbi.nlm.nih.gov/pubmed/19029902

SCIENTIFIC AMERICAN ONLINE
Find out how high school students are helping systems biologists sift through mountains of viral data at ScientificAmerican.com/may2011/systems-video

PHYSICS

The Space Station's Crown Jewel

A fancy cosmic-ray detector, the Alpha Magnetic Spectrometer, is about to scan the cosmos for dark matter, antimatter and more

By George Musser, staff editor

THE WORLD'S MOST ADVANCED COSMIC-RAY DETECTOR TOOK 16 YEARS AND $2 billion to build, and not long ago it looked as though it would wind up mothballed in some warehouse. NASA, directed to finish building the space station and retire the space shuttle by the end of 2010, said it simply did not have room in its schedule to launch the instrument anymore. Saving it took a lobbying campaign by physicists and intervention by Congress to extend the shuttle program. And so the shuttle *Endeavour* is scheduled to take off on April 19 for the express purpose of delivering the Alpha Magnetic Spectrometer (AMS) to the International Space Station.

Cosmic rays are subatomic particles and atomic nuclei that zip and zap through space, coming from ordinary stars, supernovae explosions, neutron stars, black holes and who knows what—the last category naturally being of greatest interest and the main impetus for a brand-new instrument. Dark matter is one of those possible mystery sources. Clumps of the stuff out in space might occasionally release blazes of particles that would set the detectors alight. Some physicists also speculate that our planet might be peppered with the odd antiatom coming from distant galaxies made not of matter but of its evil antitwin.

The spectrometer's claim to fame is that it can tell the ordinary from the extraordinary, which otherwise are easily conflated. No other instrument has the combination of detectors that can tease out all the properties of a particle: mass, velocity, type, electric charge. Its closest predecessor is the PAMELA instrument, launched by a European consortium in 2006. PAMELA has seen hints of dark matter and other exotica, but its findings remain ambiguous because it lacks the ability to distinguish a low-mass antiparticle, such as a positron, from a high-mass ordinary particle with the same electric charge, such as a proton.

The AMS instrument is a monster by the standards of the space program, with a mass of seven metric tons (more than 14 times heavier than PAMELA) and a power consumption of 2,400 watts. In a strange symbiotic way, it and the space station have come to justify each other's existence. The station satisfies the instrument's thirst for power and orbital reboots; the spectrometer, although it could never fully placate the station's many skeptics, at least means the outpost will do world-class research. As CERN's Large Hadron Collider plumbs the depths of nature on the ground, the Alpha Magnetic Spectrometer will do the same from orbit. SA

Time of Flight System 1

PURPOSE: Measure particle velocity and charge.
DESIGN: Sheets of transparent polymer that glows when a charged particle passes through.
OPERATION: A pair of these detectors times how fast the particle takes to cover the length of the instrument.

Magnet

PURPOSE: Bend paths of charged particles.
DESIGN: Permanent magnet with a field strength of 0.15 telsa. This magnet replaces the cryogenic superconducting magnet used in the original design, giving the instrument a longer lifetime.
OPERATION: When passing through, a positively charged particle is deflected to the left, a negatively charged one to the right.

Silicon Tracker

PURPOSE: Measure particle charge and momentum.
DESIGN: Nine planes of particle detectors.
OPERATION: The detectors trace out the path of each particle through the magnetic field.

SOURCE FOR ISS MODEL: NASA

SCIENTIFIC AMERICAN ONLINE
For more information on how the Alpha Magnetic Spectrometer works, visit **ScientificAmerican.com/may2011/ams**

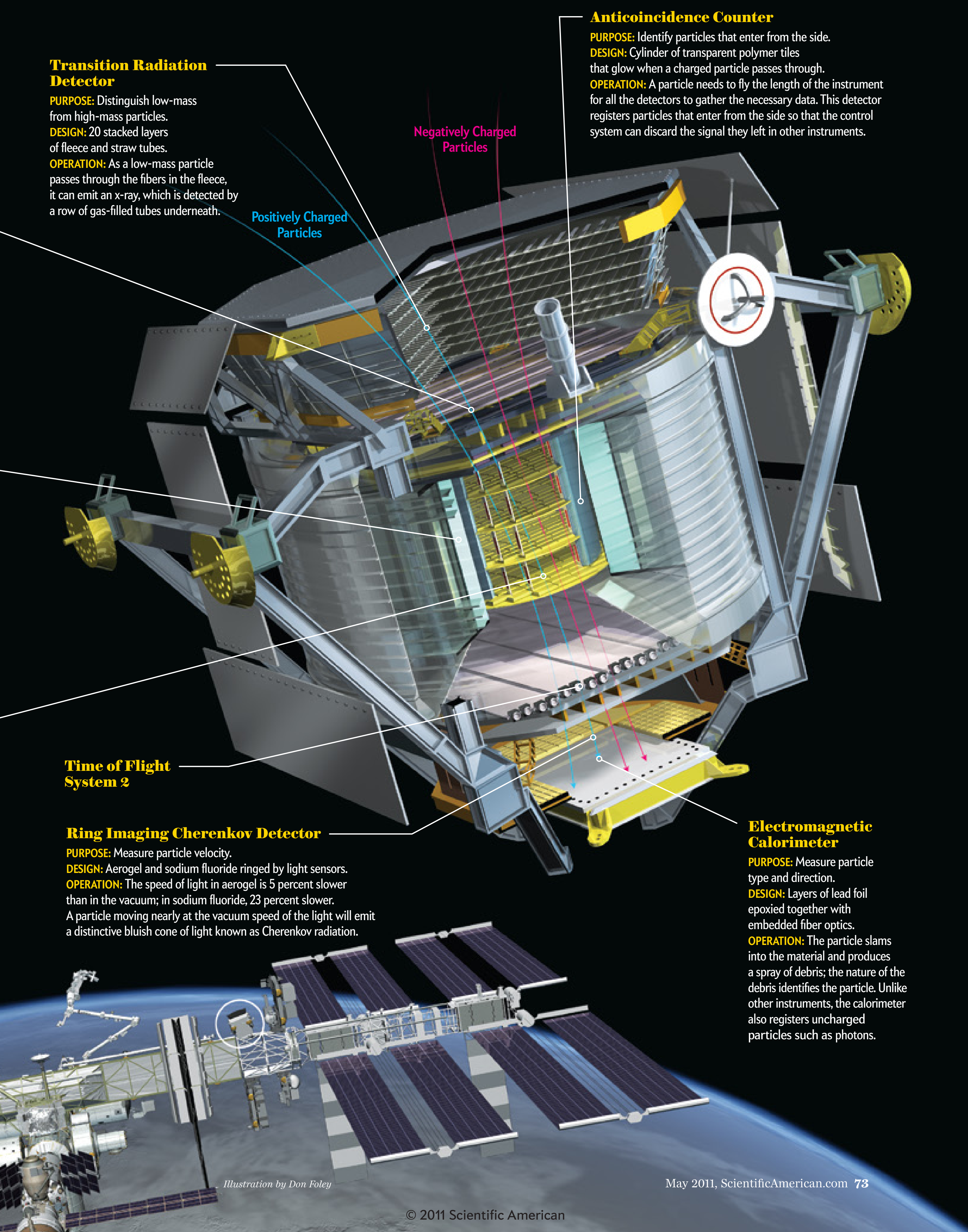


Illustration by Don Foley

AGRICULTURE

THE GROWING MENACE FROM SUPERWEEDS

Pigweed, ragweed and other monsters have begun to outsmart the advanced technologies that protect the biggest U.S. cash crops

By Jerry Adler

Back to the future: A chopping crew on a farm in Arkansas must resort to the age-old practice of hoeing to get rid of pigweed that has become resistant to glyphosate, the active ingredient in the herbicide Roundup.

IN BRIEF

Chemical herbicides keep nature at bay for only so long: weeds inevitably develop resistance to the chemicals.

Indeed, weeds have begun to become resistant to glyphosate, the key ingredient in the widely used Roundup and a chemical that the biggest cash crops have been genetically engineered to withstand.

Agricultural scientists must now seek out new strategies to protect plantings. Meanwhile some critics argue that reliance on genetic engineering should be reassessed.

Jerry Adler was a senior editor at *Newsweek* from 1979 until 2008. He has written on a wide range of topics, from profiles of Stephen Hawking and Sally K. Ride to a cover story on America's infatuation with "self-esteem."

IN THE SECOND WEEK OF NOVEMBER, CENTRAL INDIANA IS A PATCHWORK OF TAWNY AND BLACK: here a field covered with a stubble of dried corn and soybean plants; a little farther on, bare earth where the farmer has plowed under the residue of last summer's crop. This is soil that wants to grow things, and already if you look closely you can see some shoots of fall weeds: chickweed, cressleaf and purple nettle. In a greenhouse on the campus of Purdue University, Chad Brabham, a soft-spoken grad student in weed science, selects two pots, each holding one 18-inch-high plant, bearing serrated, three-lobed leaves on a coarse stem. If the plants look familiar, you might have seen them growing in a vacant lot or by a roadside almost anywhere in the lower 48 states. They are *Ambrosia trifida,* or giant ragweed—a plant as ugly as its name and as useless, well, as its cousin, common ragweed, *A. artemisiifolia,* a machine for sucking up water and spewing out highly allergenic pollen. If the farmers stopped farming, it would not take more than a few years before this part of Indiana would live up to the nickname that agronomists joke should appear on its license plates: Giant Ragweed National Forest.

Over the past half a century or so, that fate has been kept at bay primarily by chemical herbicides. One of the most widely used is glyphosate, best known as the active ingredient in Monsanto's Roundup weed killers, among others. Brabham positions the two pots in a spray chamber and fills a small tank with a solution of the potassium salt of glyphosate. A traveling spray head swiftly traverses the length of the chamber and soaks the drab-green leaves with what by all rights should be a lethal dose. Brabham removes the pots and returns them to the growing table. What happens to these weeds in the next 24 hours will show, in microcosm, what farmers will face across the Midwest this growing season.

Glyphosate has taken center stage in an emerging drama in which the weed killer is the protagonist. "I wouldn't use the word 'catastrophe,' but there are people saying it could be the worst thing for cotton growers since the boll weevil." So says Doug Gurian-Sherman, a plant pathologist and senior scientist at the Union of Concerned Scientists, discussing the spread of glyphosate-resistant weeds—aka "superweeds"—which in the past decade have expanded their range in the U.S. from a few scattered occurrences to as much as 11 million acres. This coverage is still a small fraction of the 400 million acres of U.S. cropland, but it represents a fivefold increase just since 2007. "That's a huge jump in the extent of those plants, and I don't think anyone was expecting that," says David Mortensen, a weed ecologist at Pennsylvania State University. And as he testified at a congressional hearing last summer—called by Representative Dennis J. Kucinich of Ohio to investigate the U.S. Department of Agriculture's regulation of genetically engineered seeds—"there is reason to believe this trend will continue."

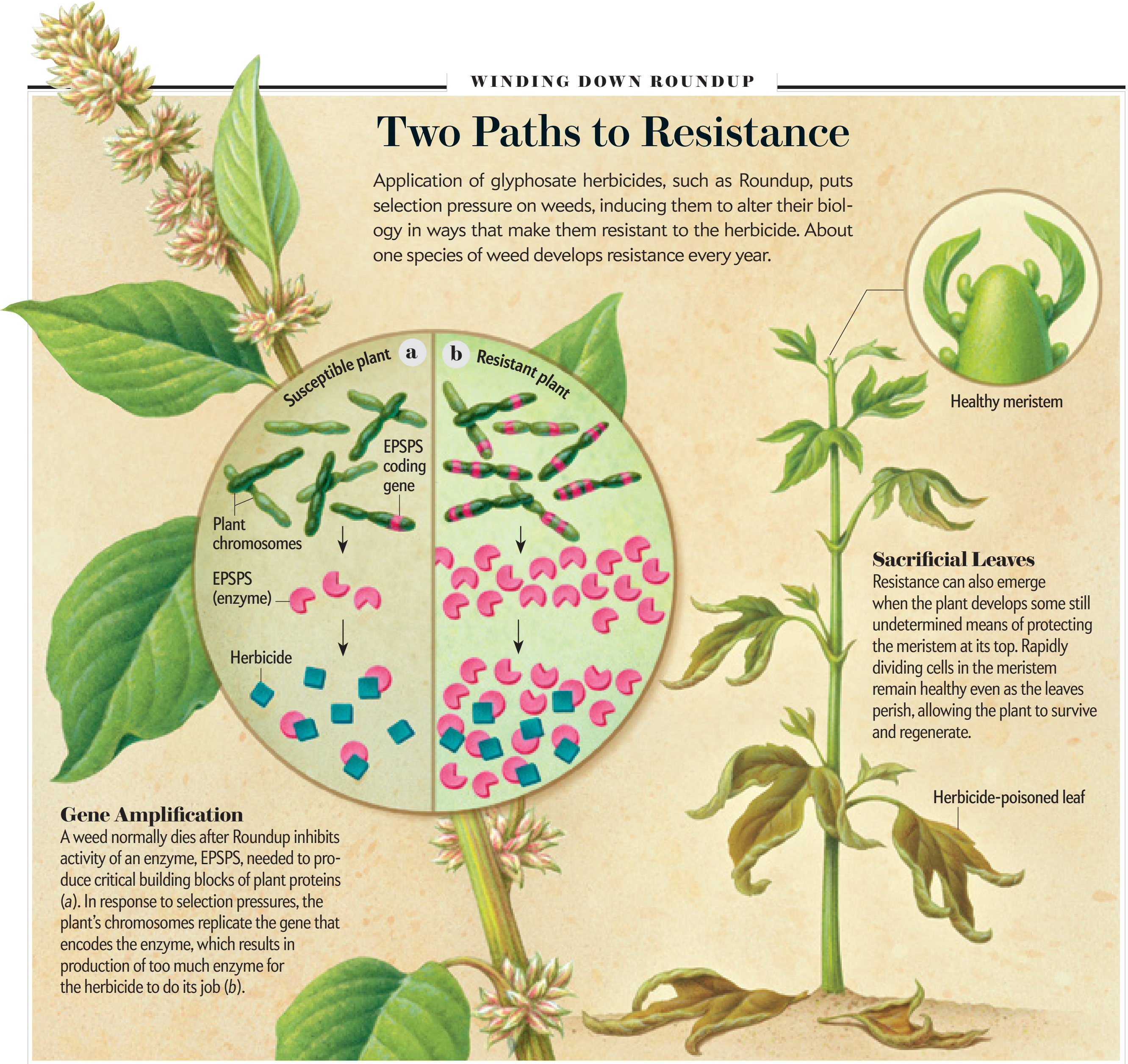
If superweeds do rise to the level of a catastrophe, it will be one that could not only have been predicted but that was also even foreseen. Like the antibiotic-resistant bacteria that have infectious disease specialists fearing the worst, it is a problem we have brought on ourselves, a reminder of the futility of attempting to outrun evolution. And more weeds are what we least need in a world that may be bumping up against the limits of technology to expand food production.

THE MAKING OF KILLER RAGWEED

THOSE WHO MOSTLY VIEW CORNFIELDS from an airplane window probably do not appreciate how much of farming consists of keeping weeds away from crops. The very word "cultivate" means not only to make something grow but also to plow or till the soil, which was the original method of weed control—uprooting unwanted plants and burying their seeds. Weeds lack the stealth and single-minded lethality of insects and microbes, which can strike seemingly out of nowhere and wipe out a crop in a matter of days. They grow in plain sight and attack their neighbors indirectly, robbing those plants of nutrients, water and, crucially, sunlight. But bugs and disease are typically sporadic, hit-or-miss events, whereas weeds are ubiquitous. Unchecked, a single giant ragweed plant can reduce the yield in an area holding 30 soybean plants by as much as half.

Which is why agronomists have been keeping a close eye on the weed species—10 at last count in the U.S. and about an equal number in the rest of the world—in which certain populations have evolved the ability to withstand an ordinarily lethal dose of glyphosate. As Monsanto spokespeople are quick to point out, that leaves more than 300 species still vulnerable to Roundup. But the 10 include some of the most prolific and intractable pests infesting cotton, corn and soybean fields: giant and common ragweed, horseweed, Johnsongrass, waterhemp and Palmer amaranth. The last, also known as pigweed, is the Paul Bunyan of weeds, able to grow a stalk as thick as a baseball bat and tough enough to disable a combine that has the misfortune to

BRAD LUTTRELL (*preceding pages*)



encounter it. In its herbicide-resistant form, "it's about the closest thing out there to a weed we can't control," says Thomas T. Bauman, a weed scientist at Purdue. "It makes giant ragweed [which itself can exceed 10 feet] look small, and it germinates all season, so after you think you've killed it off, it comes up again the next time it rains." Some cotton growers have had to abandon their fields where pigweed has taken hold. Others have turned back the clock on agriculture by a century and are sending crews into their fields to whack at it with hoes. "I've seen more hoe crews in the fields [in 2010] than the past 15 years combined," says David R. Shaw, vice president for research and development at Mississippi State University. "It's incredibly hard work," he adds, "and extremely difficult to make a profit."

It is also work that farmers in the developed world thought they had left behind, with the coming on the scene of organic herbicides after World War II. Among the earliest was 2,4-D, the first of a large class of herbicides that mimic the hormone auxin and send the plant into a lethal frenzy of uncoordinated growth. Other classes of herbicides attack other processes, such as photosynthesis or nutrient transport. Glyphosate inhibits an enzyme called EPSPS (5-enolpyruvylshikimate-3-phosphate synthase) that builds three essential amino acids in plants and bacteria but, crucial to its widespread adoption, not in animals. The chemical attacks cells in the meristem, the growth bud at the tip of the plant. Within a day of application the plant stops growing, and death typically follows within a week or two.

Unlike the auxin mimics, which selectively kill broadleaf plants but are relatively harmless to grasses, glyphosate attacks anything green. And unlike herbicides that can be spread on the soil before weeds emerge in the spring, it must be applied directly to the leaves of whatever you are trying to kill. These traits limited glyphosate's usefulness for several decades after its discovery in 1970. Farmers generally could use it only in the early spring, between the appearance of the first weeds and the sprouting of the crop, or during the growing season by the labor-intensive method of squirting it between the crop plants directly onto individual weeds. Micheal Owen, an agronomist at Iowa State University, describes weed management in those

Illustration by Cherie Sinnen

years as both art and science, a continuous juggling of herbicide application, crop rotation, and fall and spring tillage to various depths, each with a price in money and time to be weighed against the potential yield loss averted. Each technique also tended to control a different suite of weeds or, to put it another way, selected for the ones it did not kill. Those able to survive the onslaught flourished under the attack regimen. Weed problems are cumulative, as seeds mount up year after year, so the way to stay ahead was to use different techniques and change them often. Weeds thrive on predictability.

READYING A REVOLUTION

ALL THAT CHANGED in the early 1990s, when Monsanto perfected the technology to breed crops that could resist glyphosate. Whatever else one could say about this innovation, it was a scientific triumph that took, by Monsanto's estimates, 700,000 person-hours of research time. A seven-year search for the right gene ended in an outflow pipe from a Monsanto facility in Louisiana. There researchers looking for organisms that could survive amid the glyphosate runoff discovered a bacterium that had mutated to produce a slightly altered form of the EPSPS enzyme. The altered enzyme made the same three amino acids but was unaffected by glyphosate. Scientists isolated the gene that coded for it and, along with various housekeeping genes (for control and insertion of the gene for the enzyme) collected from three other organisms, implanted it in soybean cells with a gene gun.

The herbicide Roundup revolutionized the farming of commodity crops in the U.S. and around the world, particularly in Argentina and Brazil, but now increasing resistance means its days may be numbered.

This is a brute-force technology in which the selected DNA is wrapped around microscopic specks of gold that are blasted at soybean embryos, in hopes that at least a few will find their way to the right place on a chromosome. Tens of thousands of trials resulted in a handful of plants that could withstand glyphosate and pass the trait down to their descendants. Starting in 1996, Monsanto began selling these soybean seeds as Roundup Ready. Seeds for glyphosate-resistant cotton, canola and corn followed soon after.

It also was a commercial triumph. Roundup Ready seeds revolutionized the farming of commodity crops in the U.S. and around the world, particularly in Argentina and Brazil. Encouraged by Monsanto's advertising, farmers basically outsourced their weed problems, planting Roundup Ready seeds and dousing their fields with glyphosate at the first (and second and third) appearance of weeds. Last year in the U.S., 93 percent of soybean acres, and a large majority of corn and cotton, were planted with Roundup Ready seeds. Estimates of global demand in 2010 ranged up to almost one million tons.

Whether this technology has actually helped farmers produce more food is in dispute. The biotech industry likes to claim that it has, but a study by the Union of Concerned Scientists in 2009 concluded that any gains were small and far outstripped by the progress wrought by conventional breeding, at a small fraction of the cost. But the Roundup Ready system had other advantages as well. Most experts agree that among synthetic organic pesticides, glyphosate is one of the least toxic and persistent. And its effectiveness when used on Roundup Ready crops meant farmers had less need for tillage. No-till or low-till farming, a trend that began in the 1980s, saves fuel and reduces erosion and nutrient runoff into waterways. Glyphosate "is an incredibly effective chemical for killing plants," says John Lydon, chief weed scientist at the USDA, "and one of the most benign agricultural chemicals in use."

That state of affairs was, of course, too good to last. "Weeds are constantly evolving by adapting to high selection pressures imposed by crop production practices," says Purdue horticulturist Stephen Weller. Glyphosate resistance was almost unknown in the years before Roundup, but since then it has appeared in new species of weeds at the rate of about one a year. Applying the same herbicide to the same crop every year, with no other weed-control measures, creates a perfect laboratory for the evolution of resistance, Bauman says. "The resistant weed is out there. Just apply the herbicide, and you'll find it."

The first question everyone has about these glyphosate-resistant superweeds is whether they have the same resistance mechanism found in Roundup Ready seeds—that is, did the gene jump the species barrier into weeds from crops? Owen, expressing the consensus of plant biologists, says no; weeds native to the U.S. are too far apart from soybeans, corn or cotton to interbreed. (In contrast, certain plants are considered too close to their weedy relatives to run the risk of adding herbicide-resistant genes, such as creeping bentgrass, the turf of choice for golf greens.) Under the evolutionary pressure of glyphosate, weeds developed their own defenses. Resistant pigweed has the normal form of the EPSPS gene, not the altered allele engineered by Monsanto. But it has the normal gene in vastly greater numbers, from five to 160 times as many copies, which produce the enzyme in amounts that overwhelm the inhibiting effect of the herbicide.

MYSTERY SURVIVOR

BACK IN THE PURDUE GREENHOUSES, Brabham's experiment with giant ragweed demonstrates yet another kind of resistance, which appears to have also evolved independently. In susceptible weeds, the effects of glyphosate show up first in the rapidly dividing cells of the meristem. (The chemical also travels to the roots, where it may interfere with resistance to fungi; plants are notoriously hard to autopsy, but shriveled and rotted roots are often noted after spraying with glyphosate.) But when Brabham examines his specimens 18 hours after spraying, he sees something very different: the big leaves have begun to curl and brown, but the meristem is green and healthy. The plant appears to be segregating the herbicide in the leaves, which over the next week or two will die and fall off. But the plant will survive and regenerate from the meristem. "I'd love to know what's causing that," Weller says, "because you see the same thing in pathogen resistance. The leaf dies, but it doesn't spread to the rest of the plant. That's something we could really make use of, if we knew how it does it."

It is important to remember, Weller says, that Monsanto's Roundup Ready technology did not cause this problem by itself;

Foe in foliage: Weedy enemies of the midwestern farmer include (*left to right*) giant ragweed, horseweed and Johnsongrass, all of which have developed some level of resistance to Roundup.

the weeds evolved resistance to glyphosate on their own. But the availability of seeds for glyphosate-resistant crops enabled farmers to take the path of least resistance, which was to douse their fields with Roundup to the exclusion of other weed-control techniques and chemicals. They could have taken a lesson from medicine, which relies on a multiple-drug strategy to control fast-mutating viruses such as HIV; the odds are very much against a single organism spontaneously evolving resistance to several different chemicals at once, so ideally there are no survivors. It is fair to say that Monsanto, with a huge investment to recoup, did not exactly discourage them. "[Glyphosate resistance] could have been avoided, or at least put off for a long time, if farmers had used another herbicide in combination," muses Glenn Nice, a Purdue extension agent who deals with farmers around the state regularly. "But farming is a business like any other." Actually, not exactly like any other: farmers make their money at the margins—that is, after defraying expenses—and their efforts are constrained not just by cost but by the length of a day and a growing season. "An ounce of prevention is worth a pound of cure," Nice adds, "but you still have to pay for the ounce."

And farmers will be paying. Biotech and chemical companies are hard at work inserting genes for resistance to other herbicides into crops. Monsanto hopes to market, within the next year or two, seeds for plants resistant to an herbicide called dicamba, and Dow has developed a gene for resistance to 2,4-D. The traits will be "stacked" along with Roundup Ready genes onto a new generation of genetically engineered seeds, so that farmers can broadcast two herbicides on their fields, together or sequentially, rather than relying just on glyphosate. DuPont already sells seeds with resistance to glyphosate and another herbicide, glufosinate. That is in addition to other engineered traits bred into commercial seeds, such as the gene for Bt, a naturally occurring insecticide.

This is a prospect many agronomists greet warily. Dicamba and 2,4-D are older chemicals whose use has been grandfathered in under federal regulations; both are considered more toxic and persistent than glyphosate and might not easily get through the registration process if they were introduced today. Dicamba, in particular, has a tendency to volatilize after application, drift and settle on neighboring fields, where it has been known to damage other crops or wild vegetation. And there is the question, still unanswered, of how many added traits you can load onto a seed before you begin to impair the plant's vigor and productivity. Every additional thing you ask of an organism takes energy away from what it is supposed to be doing in the first place—in this case, growing food.

The bigger question has to do with the future of agriculture and how farmers will feed a growing and increasingly affluent and urban world population. "This is a silver-bullet, industrial approach, not an agroecosystem approach," Gurian-Sherman says. With a population of glyphosate-resistant weeds already established in many places, it is virtually certain that if dicamba and 2,4-D are used the same way, some of the same weeds will evolve resistance to them as well. Then where will we turn? There are only so many herbicide families, and chemical companies are not developing new ones, because the returns are so much better on genetic engineering of seeds. "I'm not opposed to genetic engineering in principle, but where has it gotten us?" he asks. "Billions in research have produced only two helpful traits [glyphosate resistance and Bt expression], whereas conventional techniques have yielded insect and disease resistance, drought tolerance and better crop yields at a lower cost."

The solution, Gurian-Sherman argues, lies not with more expensive technological fixes but with the kind of crop science that would have been familiar to Gregor Mendel in the 19th century: incremental advances in yield, drought resistance and fertilizer use. "We need a fundamental shift in how we think about agriculture," he says, "and this isn't getting us any closer to it." SA

MORE TO EXPLORE

Failure to Yield: Evaluating the Performance of Genetically Engineered Crops. Doug Gurian-Sherman. Union of Concerned Scientists, April 2009.

The Impact of Genetically Engineered Crops on Farm Sustainability in the United States. Committee on the Impact of Biotechnology on Farm-Level Economics and Sustainability, National Research Council. National Academies Press, 2010.

SCIENTIFIC AMERICAN ONLINE
More sources on superweeds at ScientificAmerican.com/may2011/superweeds

Masters

# of Disguise

Animal mimicry takes many forms—including chemical and acoustic varieties—and offers unique insights into evolution

By Peter Forbes

The year was 1848. A young British naturalist named Henry Walter Bates had gone to the Amazon with fellow countryman Alfred Russel Wallace to look for evidence of the origin of species. Over the course of his 11-year stay, he noticed that local relatives of a European butterfly known as the cabbage white—the pierids—were bedecked in the showy reds and yellows of rain forest butterflies called heliconids. Observing that the heliconids seemed to possess toxins that made them unpalatable to predators, Bates reasoned that by mimicking the toxic heliconids' warning colors, the harmless pierids were escaping predation. When Bates returned to England in 1859, the year that Charles Darwin published *On the Origin of Species,* his discovery of these "mockers," as he called them, became the first independent evidence to corroborate Darwin's theory of evolution by natural selection—which holds that organisms best able to meet the challenges in their environment

BEHAVIORAL MIMICRY

Shape Shifter

Thaumoctopus mimicus, the so-called mimic octopus from Indonesia (*left*), masquerades as a flounder (*below*), holding its arms together to copy the flatfish's shape and undulating them to replicate its mode of swimming.

survive to produce the most offspring, so that their traits become increasingly common through the generations.

Apart from Darwin and Bates, though, most biologists were slow to recognize the significance of nature's impersonators. But now, a century and a half later, mimicry is fast becoming a model system for studying evolution. It is ideally suited to this task because both the selection pressure (predation) and the traits under selection are clear. Indeed, mimicry demonstrates the process of evolution in its most stripped-down form. Discovery of new types of mimicry has also helped fuel fresh interest in the phenomenon among biologists. Joining the classic examples familiar from high school biology class—such as the scarlet kingsnake, whose coloring resembles that of the eastern coral snake, or the viceroy butterfly, whose wing pattern matches the monarch's—are chemical, acoustic and even behavioral mimics. And stunningly, genetic analyses of one group of mimics have revealed a mechanism by which new species can arise.

BEYOND VISUAL MIMICRY

INITIALLY MIMICRY WAS REGARDED as a strictly visual affair, of the kind evident in Bates's colorful Amazonian butterflies. But it turns out that mimics may fool their foes in other modes. For insects, chemical communication is often more important than the visual variety, and many predators eavesdrop on these chemical conversations for their own ends. The large blue butterfly (*Maculinea arion*) found across northern Europe and Asia is one notable example. In the 20th century the large blue suffered dramatic declines in many areas and became extinct in Britain in 1979, despite attempts to save it. Agonizingly, that was the very year Jeremy Thomas of the University of Oxford began to realize why conservation efforts had failed: the large blue's survival depended on the survival of an ant species it mimicked.

In Britain, large blue caterpillars begin life eating thyme plants on warm chalk slopes whose grasses the sheep, rabbits and other grazers keep close-cropped. After the caterpillars molt for the third time, they drop off the thyme plants to the ground, where they launch their false-advertising campaign. The fallen caterpillars emit a chemical signal to attract local ants, tricking them into treating the caterpillars as one of their own. The bamboozled ants carry the caterpillar back to their underground nest, where it proceeds to feast on their larvae for the next 10 months, after which it begins its metamorphosis and eventually emerges aboveground as a butterfly.

Although several species of ants take the caterpillars into their nests, the caterpillars fare well only in the nests of a species of red ant called *Myrmica sabuleti*. And these ants thrive only when the grass on the chalk slopes is short, allowing enough sunlight in to keep them sufficiently warm. Thomas figured out that as grazing subsided, the grass grew too long for the *M. sabuleti* ants. As they disappeared, so, too, did the large blue.

IN BRIEF

Mimicry among Amazonian butterflies offered the first independent evidence for Charles Darwin's theory of evolution by natural selection.

Recently biologists have become interested anew in nature's con artists, both as a result of the discovery of additional types of mimics and because the phenomenon provides an ideal system for studying evolution.

Studies of the genes and behavior of one group of mimics have in fact revealed a mechanism for the origin of new species.

Peter Forbes is a London-based science writer. His latest book, *Dazzled and Deceived: Mimicry and Camouflage,* has won the 2011 Warwick Prize for Writing. This is his second article for *Scientific American.*

Thanks to Thomas's revelation, scientists were able to reintroduce the butterfly to Britain in the 1980s and help it and the *M. sabuleti* ants to flourish through careful management of the turf. By 2008, 32 colonies had been established in southwestern England, the largest of which contained 1,000 to 5,000 butterflies per hectare. But one mystery remained: the ants do not just tolerate the caterpillars they bring home; they treat them like royalty, killing their own larvae and feeding them to the caterpillars if food is scarce. In 2009 Thomas determined why. Writing in *Science,* he reported that in addition to copying the ant's chemical signal, the caterpillars replicate an acoustic cue. Specifically the caterpillar somehow mimics a tiny noise the queen ant makes, assuring itself a steady food supply. By mastering two key impressions, the large blue tricks the ants into seeing it not just as one of their own but as the most important member of their society.

The large blue butterfly's subterfuge is not the only instance of acoustic mimicry. This kind of imitation also occurs in one of nature's classic arms races: the struggle between moths and bats. Bats hunt at night using echolocation, emitting ultrasound clicks and detecting the echoes of these sounds as they bounce off objects in the environment. The result is an aural image of their surroundings—including any tasty moths in the vicinity. This tactic is so efficient that moths have had to develop countermeasures to survive.

Like many day-flying butterflies, some night-flying moths gather toxic chemicals from plants that make them baneful to bats. But whereas a diurnal insect can advertise its toxicity with warning coloration, that strategy would not work for a nocturnal moth trying to avoid a predator hunting in the dark. Tiger moths have evolved especially ingenious solutions to this problem: they emit warning clicks that the bats learn to associate with unpalatable prey. Not all these tiger moth species are actually noxious. But as William Conner of Wake Forest University has found in his experiments, once a bat eats a toxic tiger moth, it will subsequently tend to avoid other sound-producing tiger moths, including perfectly edible ones.

The moths have yet another acoustic trick. In 2009 Conner's group reported in *Science* that the more subtly tuned clicks of the edible tiger moth *Bertholdia trigona* throw the bats' echolocation mechanism into disarray: the bats attempt to catch the moths but fail. This is true radar jamming, of the kind found in modern fighter planes.

In addition to hoodwinking predators through their coloration, scent or sound, mimics may attempt to con the enemy by assuming the shape of another species. In 1998 biologists working in Indonesia announced the discovery of a small octopus with an arsenal of disguises—*Thaumoctopus mimicus,* the mimic octopus. Like most octopuses (and their squid and cuttlefish kin), the Indonesian species can change color to blend in with its surroundings. But it was also reputed to do impressions of a menagerie of marine creatures found in the same waters as the octopus—including the lion fish, the banded sea snake and the flounder—not only copying the coloration of these animals but also changing its comportment to mimic their shapes.

PRECEDING PAGES: MICHAEL AW (*octopus*); NORBERT WU *Corbis* (*octopus as flounder*)

Heliconius cydno **butterflies with mutant yellow wing coloration instead of the normal white prefer yellow mates because the gene for wing color is linked to the gene for mate choice. In Costa Rica the yellow form has evolved into a separate species, *H. pachinus.***

COURTESY OF MARCUS KRONFORST *Harvard University*

So far most of these impressions remain speculative. But in 2008 octopus expert Roger T. Hanlon of the Marine Biological Laboratory in Woods Hole, Mass., reported in the *Biological Journal of the Linnean Society* that he had found strong evidence that the mimic octopus does indeed impersonate the flounder, holding its tentacles together in a flat, flounderlike shape and swimming in the flounder's undulating way.

EVIDENCE FOR EVOLUTION

MIMICRY RESEARCH HAS, for the most part, focused on the mimetic signal and the way it is received. But for one group of creatures—the *Heliconius* butterflies that enthralled Bates in the 1850s—we now have a fuller picture: the genetics underlying their dazzling array of mimetic patterns. Armed with this new understanding, scientists have uncovered something that surely would have delighted Darwin no end: a mechanism for the very beginning of speciation, the process by which one population of a species becomes reproductively isolated (unable to mate with other populations) and gives rise to a new species.

The discovery has its roots in research that began about 10 years ago with the work of Chris Jiggins, now at the University of Cambridge, who determined that in addition to being mimetic, *Heliconius* wing patterns serve another purpose: males use them to identify potential mates. In 2009 Jiggins, working with Mauricio Linares of the University of the Andes in Colombia, described research that illustrates just how dramatic the effects of the interplay between mimicry and mate choice can be. By crossing *H. melpomene* butterflies with *H. cydno* ones, Linares managed to breed a hybrid in three generations that exhibited the wing pattern of a wild *H. heurippa*. In mate choice experiments this hybrid, which had in a sense just evolved, instantly preferred individuals with its own wing pattern to those bearing the different wing patterns of the parent species.

Later that year Marcus Kronforst of Harvard University published a paper in *Science* advancing that line of research one crucial step further. He demonstrated that the gene for wing color in *Heliconius* is inherited with the gene for mate choice. That link accounts for the instant preference the artificial hybrid butterflies showed for their doppelgängers. This relation between wing color and mate choice provides a mechanism by which speciation can occur. In a given population of *Heliconius* butterflies, a mutation leading to a beneficial wing pattern can spread quickly because the mutants prefer to mate with their own kind. Over time two forms that could interbreed but generally choose not to will accumulate other genetic variations that eventually result in the sterility of any offspring produced by their union. Their reproductive isolation complete, two species will exist where once there was one (or in the case of Linares's butterflies, three species will exist where once there were two).

Working with two populations of *H. cydno* in Ecuador and Costa Rica, Kronforst has identified the two "ends" of this speciation process. In Ecuador the white and yellow butterflies are two varieties of the same species, *H. cydno,* separated only by differences in a single gene that flips the wing color from white to yellow. These butterflies appear to be at the very earliest stage of speciation. Their counterparts in Costa Rica, in contrast, have diverged to the point where the yellow form qualifies as a separate species, *H. pachinus*. Although these two Costa Rican species can still interbreed in captivity, the resulting hybrids exhibit small differences in the wing patterns that render them liable to predation. Presumably genetic differences between these two species will continue to accumulate over time such that they will eventually not be able produce viable offspring at all.

Back in 1863, Bates prophesized that "the study of butterflies—creatures selected as the [exemplars] of airiness and frivolity—instead of being despised, will someday be valued as one of the most important branches of Biological science." The work of Jiggins and Kronforst and their colleagues has realized that prediction. No doubt the study of other mimics will yield more such insights into the inner workings of evolution. SA

MORE TO EXPLORE

Acoustic Mimicry in a Predator–Prey Interaction. Jesse R. Barber and William E. Conner in *Proceedings of the National Academy of Sciences USA,* Vol. 104, No. 22, pages 9331–9334; May 29, 2007.

Mimicry and Foraging Behaviour of Two Tropical Sand-Flat Octopus Species off North Sulawesi, Indonesia. Roger T. Hanlon et al. in *Biological Journal of the Linnean Society,* Vol. 93, No. 1, pages 23–38; January, 2008.

Polymorphic Butterfly Reveals the Missing Link in Ecological Speciation. Nicola L. Chamberlain et al. in *Science,* Vol. 326, pages 847–850; November 6, 2009.

SCIENTIFIC AMERICAN ONLINE
See a slide show of animal mimics at ScientificAmerican.com/may2011/forbes

CREATIVITY

Inner Sparks

Hearing specialist and sax player Charles J. Limb says that studying the brain during flights of improvisation may provide new understanding of creativity—as well as insight into the musical genius of John Coltrane

Interview by Alicia Anstead

CHARLES J. LIMB MIGHT HAVE BEEN A JAZZ SAXOPHONIST. HE GREW UP IN A MUSICAL family and showed early signs of talent. He idolized John Coltrane and, as a student at Harvard, directed a jazz band. Although he ultimately went to medical school, he chose his specialty (otolaryngology) in part because of his musical interest. As a hearing specialist and surgeon at Johns Hopkins Medical Center, he performs cochlear implants in patients to restore hearing and enable the deaf to appreciate music. His sensibility and passion as an artist continue to inform his research. At least half of his studies during the past 10 years have focused on regions of the brain activated during moments of deep creativity. As he puts it, he wants to understand what went on in Coltrane's head when he performed brilliant improv on his sax night after night.

Limb and National Institutes of Health neurologist Allen R. Braun have developed a method for studying the brains of highly skilled jazz musicians while they are creating music. Subjects play on a nonmagnetic keyboard as they lie in a functional magnetic resonance imaging (fMRI) machine that takes pictures of their brain. Then the scientists compare neural activity during improvisation with what happens when playing a memorized piece. Limb can also interact with the musician in the scanner by playing on an external keyboard—or, as musicians put it, exchanging riffs.

Limb's work is fueled in part by a determination to understand the implications for transforming education and for encouraging everyone to live purposely creative lives. Excerpts follow:

Why should scientists study creativity?
While I think creativity is amazing, I don't put it on a pedestal. I view at it as a very normal biological process that some peo-

IN BRIEF

WHO
CHARLES J. LIMB

VOCATION/AVOCATION
Surgeon; ear, nose and throat specialist; sax player

WHERE
Johns Hopkins Medical Center and nightclubs and theaters in the Baltimore/D.C. area

RESEARCH FOCUS
What goes on in the brain when musicians improvise?

BIG PICTURE
Creavity is a whole-brain activity that is deeply related to our sense of self. It behooves us to understand it.

Photograph by Stephen Voss

ple are able to take to extremely profound levels but that fundamentally is a basic requirement of human civilization and how we advance. It infiltrates every aspect of human life. I don't know that there's an attribute that is more responsible for how we've evolved as a species than creativity.

From a scientific perspective: if it's a biological behavior, if humans are creative beings, we really ought to study it like you study any other complex biological behavior. Furthermore, because it does seem to be important, not just for the arts but for life, it's probably something we should understand better.

Why is improvisation an ideal activity for studying creativity?

There are a lot of forms of creativity. For scientific study, what you really need is the behavior that is a prototypical creative act, realizing that it doesn't represent all creative behavior. Writing a novel is a creative act, but it's hard to do that in an fMRI scanner, and something that takes a year or so to do is hard to study. Musical improvisation is spontaneous. The timescale is relatively concise, meaning that every time you do it, you can constrain it to a time frame quite reasonably and expect artistically relevant results. That's a natural task for a musician. So the timescale is natural for a scientific experiment.

What kinds of challenges did you face in trying to summon creativity on demand? Musicians don't usually find a muse in a science lab.

The musicians were a self-selected bunch. I didn't coerce them to participate. They were all into the idea. The experience is foreign for the first minute or two, and then it becomes surprisingly comfortable. You're in a tube, and it's dark, and you have only headphones—it's almost like a sensory deprivation chamber where the only thing you're doing is playing piano. It's really a strange environment for playing piano, but there's not a lot to distract you. In fact, I think the music is very comforting in that setting because it's the one normal thing about the setting. The sound quality of the piano we used isn't the best. It's noisy as heck in that room. But none of the musicians complained, and they were able to play pretty well. Sometimes musicians felt embarrassed that they weren't able to play the way they normally play, but from my perspective they played very well.

Tell us about the keyboard you used in your experiments and how you adapted it to work with fMRI.

The main issues to do this are ergonomic and magnetic. You have to have a keyboard that works when you're in a narrow tube, on your back. I went into the scanner myself many times and thought about what would be the best way to make this work out. We decided the piano should be on your lap, with your hands at a natural angle in front of you, but your eyes—because you're lying down—could not be looking down. We used mirrors, so you look up at one mirror that points to another mirror that is pointed at the keyboard. In the end, you're looking at your hands even though you're looking straight ahead.

The dimension of the tube is such that we could have only 35 keys. I wanted to make them full-size so that the players would feel relatively natural. I was working with an engineer who designs MRI-compatible devices, and he and I shipped this device across the country probably 10 times to tweak it. It was a two-year process. What we had to design was a MIDI keyboard—for musical instrument digital interface—so the piano makes no noise. Every time you press a note, it sends a digital message to a computer saying a certain note was pressed. I used a program called Logic Pro, which has a piano emulator. When you press a certain note, the computer program plays the note back through headphones. When you're doing it, it feels very much like you're playing a piano naturally.

What happens neurologically to the brain during creativity?

As far as my studies have revealed, creativity is a whole-brain activity. When you're doing something that's creative, you're engaging all aspects of your brain. During improvisation, the prefrontal cortex of the brain undergoes an interesting shift in activity, in which a broad area called the lateral prefrontal region shuts down, essentially so you have a significant inhibition of your prefrontal cortex. These areas are involved in conscious self-monitoring, self-inhibition, and evaluation of the rightness and wrongness of actions you're about to implement. In the meantime, we saw another area of the prefrontal cortex—the medial prefrontal cortex—turn on. This is the focal area of the brain that's involved in self-expression and autobiographical narrative. It's part of what is known as a default network. It has to do with sense of self.

What implications does your work have for, say, education?

If we can understand what actually changes in the brain to perhaps reduce conscious self-monitoring—what a lot of expert musicians are doing and what amateur musicians are unable to do—that's a pretty interesting target for someone to consider when trying to learn to become an improviser. I think that has implications for describing what gives rise to excellent improvisation and what experts do naturally. How a teacher can take that and utilize it in a lesson is another thing entirely, but I think there's food for thought.

A number of researchers are investigating creativity right now. Why do you think this convergence of interest is taking place?

We have some new methods of analyzing brain activity and brain function that are allowing us to ask questions that were probably off-limits for scientists. And I think that says a lot about the way scientists are in general. Scientists are, for the most part, a pretty conservative bunch. They're not the kinds that want to answer the riskiest questions in terms of art. There are too many variables, it's hard to explain, and there's not a lot of grant funding. It's not disease-based, etcetera. Now we are seeing that, okay, these are legitimate questions to ask, and we have legitimate methods to try to answer the questions. We need to learn how creativity affects the brain and how to implement creativity in edu-

Keys to creativity may emerge from imaging musicians' brains.

cational systems, how to encourage children to be creative.

How do you respond to skeptics and critics who call fMRI research high-tech phrenology?

That's an interesting criticism. There's a big difference between saying that the scalp is shaped a certain way and saying that an area of the brain is physiologically active. What we're really trying to do is take a glimpse into an artist's brain while he is doing something that is unique. Keep in mind the method we use for this—fMRI—is a very, very inferential method. It is completely imprecise on so many levels, and at best you are inferring a pattern of activity that is associated with a pattern of behavior. Every method has its intrinsic limits, and that's how it should be. And in the end, what you want or hope for is that a lot of different methods, not just fMRI, are applied to the same question so that you can see converging data.

There's a reason why we're using fMRI, however. It shows us a lot of things that we've never been able to actually see before, which is human behavior in its most complex forms happening in real time. But I'm a very big critic of anyone who thinks fMRI holds the answer to everything. Having used it, I know it doesn't. On the other hand, that doesn't mean that we shouldn't extract what we can. I mean, it's a cool method.

What are the implications of your creativity research for your work as a surgeon and for cochlear implants?

In truth, the reason why I do what I do is because I love music. That is why I wanted to become a hearing specialist. That led me to treat surgical disorders of hearing primarily. Cochlear implantation is probably the best treatment that has ever existed for a profound sensory impairment, meaning there is no other sense that can be restored right now like hearing can be with a cochlear implant. These things are amazing technologically. Yet they're also very limited. What they are amazing at is producing language for people who have had intact hearing for most of their lives or for people who are born deaf and gain hearing through implants.

But music is another piece entirely. Most people who have a cochlear implant just can't hear music well. A large portion of my research goes toward trying to understand the limitations of music perception in deaf people who are hearing with cochlear implants. And I'm hoping to try to improve that. So that is a large part of what I study as well.

For me, the two parts of my work are motivated by the same idea of bringing the sublime to the deaf. The idea of going from deaf to Beethoven's Symphony no. 9 is pretty remarkable. I would love to be able take somebody there.

What's next in your creativity research?

The "trading fours" research, in which I exchange riffs with a musician in the scanner, is still ongoing, as are the studies of freestyle rappers, which I believe represents the first-ever neuroscientific study of hip-hop. The next real direction I'm headed into has to do with trying to clarify our study of reward mechanisms in the brain and their relation to creativity. Why is it that we like to be creative? Why is it that we like to perceive creativity? And what happens when somebody is improvising in terms of pleasure or reward centers? Where is the gratification neurologically, and how does that change according to the emotional content of the music? I've always wondered: Why do we love sad music? Why does it make us feel better and not worse? It's a funny inversion that takes place in the brain. Whereas we try to avoid sadness in life, in art, and especially in music, we almost gravitate toward it. By and large, the effect is very positive. Improvisation causes a similar response: When you're spontaneously creating music that is sad, what are you getting? Are you getting joy? Pleasure? What's the basis of the reward? That's one of the directions I'm heading.

What's your best answer to how Coltrane continually improvised masterpiece after masterpiece?

My best answer, honestly, is that he practiced. He was an obsessive—he practiced obsessively, even after a gig. He would play a gig and then go back to his hotel room and practice. And he was, I think, obsessed with an idea that was well beyond a performance, well beyond what a critic or a listener thought. He was really after some sort of musical perfection: the ability to have an idea that he had never had before, have that idea be profound and, at the same time, be able to execute that idea. That's a remarkable trio of goals to have right there. I think he knew that the only way he would even come close was to keep that horn in his mouth. SA

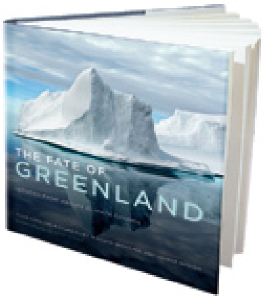
Alicia Anstead *is editor in chief of the national magazine* Inside Arts *for the Association of Performing Arts Presenters in Washington, D.C., and is a contributing editor to Harvard Arts Beat, a blog for Harvard University's Office for the Arts.*

MORE TO EXPLORE

A biography of Charles J. Limb and a selected publications list on the Johns Hopkins Medicine Web site: www.hopkinsmedicine.org/otolaryngology/our_team/faculty/limb.html

Limb's much noted "Your Brain on Improv" presentation at a TED conference: www.ted.com/talks/charles_limb_your_brain_on_improv.html

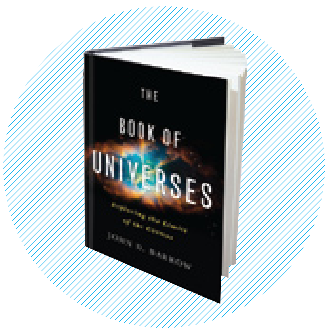
SCIENTIFIC AMERICAN ONLINE
A video of Limb and his work can be accessed at ScientificAmerican.com/may2011/anstead-limb



The Fate of Greenland: Lessons from Abrupt Climate Change

by Philip W. Conkling, Richard Alley, Wallace Broecker and George Denton. MIT Press, 2011 ($29.95)

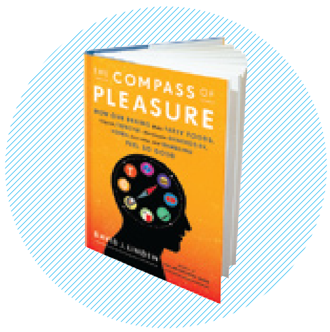
Spanning more than 600,000 square miles, Greenland's ice sheet is the largest outside Antarctica. But it is melting fast, with the thunderous sounds of icebergs calving off glaciers filling the air. This is not the first time Greenland has undergone abrupt climate change. Comparatively balmy temperatures in the 10th century allowed Norse settlers to colonize the area; the ensuing Little Ice Age coincided with their disappearance. In this book, illustrated with dramatic color photographs, four leading climate experts chronicle Greenland's climate history and discuss what the current warming means for this frozen place and for the rest of the world.



The Book of Universes: Exploring the Outer Limits of the Cosmos

by John D. Barrow. W. W. Norton, 2011 ($26.95)

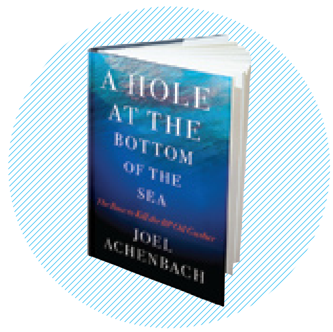
Universes that spin, ones that occupy black holes, ones that permit time travel—these are but a few of the bizarre types of universes that modern physics tells us exist parallel to our own. John D. Barrow, professor of mathematical sciences and director of a public outreach math program at the University of Cambridge, takes readers on an armchair tour of these exotic corners of the cosmos and explains how they might all be part of a single "multiverse."



The Compass of Pleasure: How Our Brains Make Fatty Foods, Orgasm, Exercise, Marijuana, Generosity, Vodka, Learning, and Gambling Feel So Good

by David J. Linden. Viking, 2011 ($26.95)

Pleasure takes many forms—from runner's high to the rush from winning big at the casino—each of which activates pleasure circuitry in the brain. Neuroscientist David J. Linden of Johns Hopkins University examines the neurobiology of pleasure and explains, among other things, how the brain's reward system can backfire, leading to addiction.



A Hole at the Bottom of the Sea: The Race to Kill the BP Oil Gusher

by Joel Achenbach. Simon and Schuster, 2011 ($25.99)

It is one of the worst ecological disasters in U.S. history: on April 20, 2010, the Deepwater Horizon oil rig exploded, killing 11 workers and unleashing a gusher of crude oil into the Gulf of Mexico. By the time engineers plugged the Macondo well on September 19, nearly five million barrels of crude had fouled the Gulf. *Washington Post* writer Joel Achenbach looks at what went wrong and how engineers eventually figured out how to kill Macondo.

ALSO NOTABLE

Science-Mart: Privatizing American Science, by Philip Mirowski. Harvard University Press, 2011 ($39.95)

A Planet of Viruses, by Carl Zimmer. University of Chicago Press, 2011 ($20)

Bottled Lightning: Superbatteries, Electric Cars, and the New Lithium Economy, by Seth Fletcher. Hill and Wang, 2011 ($26)

The Quantum Story: A History in 40 Moments, by Jim Baggott. Oxford University Press, 2011 ($29.95)

EXHIBITS

The World's Largest Dinosaurs. April 16, 2011–January 2, 2012, at the American Museum of Natural History in New York City.

Suited for Space. April 6–September 25 at the Museum of Science and Industry in Chicago.

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Michael Shermer is publisher of *Skeptic* magazine (www.skeptic.com). His next book is *The Believing Brain.* Follow him on Twitter @michaelshermer

Extrasensory Pornception

Does new research prove paranormal precognition or normal postcognition?

Psi, or the paranormal, denotes anomalous psychological effects that are currently unexplained by normal causes. Historically such phenomena eventually are either accounted for by normal means, or else they disappear under controlled conditions. But now renowned psychologist Daryl J. Bem claims experimental proof of precognition (conscious cognitive awareness) and premonition (affective apprehension) "of a future event that could not otherwise be anticipated through any known inferential process," as he wrote recently in "Feeling the Future" in the *Journal of Personality and Social Psychology.*

Bem sat subjects in front of a computer screen that displayed two curtains, behind one of which would appear a photograph that was neutral, negative or erotic. Through 36 trials the subjects were to preselect which screen they thought the image would appear behind, after which the computer randomly chose the window to project the image onto. When the images were neutral, the subjects did no better than 50–50. But when the images were erotic, the subjects preselected the correct screen 53.1 percent of the time, which Bem reports as statistically significant.

Bem calls this "retroactive influence"—erotic images ripple back from the future—or as comedian Stephen Colbert called it when he featured Bem on his show *The Colbert Report,* "extrasensory pornception."

COMMENT ON THIS ARTICLE ONLINE
ScientificAmerican.com/may2011

For many reasons, I am skeptical. First, over the past century dozens of such studies proclaiming statistically significant results have turned out to be methodologically flawed, subject to experimenter bias and nonreproducible. This assessment by University of Amsterdam psychologist Eric-Jan Wagenmakers appeared along with Bem's study in the same journal.

Second, Bem's study is an example of negative evidence: if science cannot determine the causes of *X* through normal means, then *X* must be the result of paranormal causes. Ray Hyman, an emeritus professor of psychology at the University of Oregon and an expert on assessing paranormal research, calls this issue the "patchwork quilt problem" in which "anything can count as psi, but nothing can count against it." In essence, "if you can show that there is a significant effect and you can't find any normal means to explain it, then you can claim psi."

Third, paranormal effects, which are rarely allegedly detected at all, are always so subtle and fleeting as to be useless for anything practical, such as locating missing persons, gambling, investing, and so on. Fourth, a small but *consistent* effect might be significant (for example, in gambling or investing), but according to Hyman, Bem's 3 percent above-chance effect in experiment 1 was not consistent across his nine experiments, which measured different effects under varying conditions.

Fifth, experimental inconsistencies plague such research. Hyman notes that in Bem's first experiment, the first 40 subjects were exposed to equal numbers of erotic, neutral and negative pictures. Then he changed the experiment midstream and, for the remaining subjects, just compared erotic images with an unspecified mix of all types of pictures. Plus, Bem's fifth experiment was conducted before his first, which raises the possibility that there might be a post hoc bias either in running the experiments or in reporting the results. Moreover, Bem notes that "most of the pictures" were selected from the International Affective Picture System, but he does not tell us which ones were not, why or why not, or what procedure he employed to classify images as erotic, neutral or negative. Hyman's list of flaws numbers in the dozens. "I've been a peer reviewer for more than 50 years," Hyman told me, "and I can't think of another reviewer who would have let this paper through peer review. They were irresponsible."

Perhaps they missed what psychologist James Alcock of York University in Toronto found in Bem's paper entitled "Writing the Empirical Journal Article" on his Web site, in which Bem instructs students: "Think of your data set as a jewel. Your task is to cut and polish it, to select the facets to highlight, and to craft the best setting for it. Many experienced authors write the results section first."

Bem has responded (www.dbem.ws), but I have a premonition his precognition was a postcognition. SA

Illustration by John Cuneo

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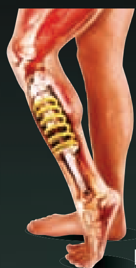
Customer Satisfaction Speaks for Itself!
4 out of 5 customers purchase a 2nd pair within 3 months.



Wear them and you'll know

That's what my doctor recommended. He said, "Gravity Defyer shoes are pain-relieving shoes." He promised they would change my life–like they were a fountain of youth. "They ease the force of gravity, relieving stress on your heels, ankles, knees and back. They boost your energy by propelling you forward." The longer he talked, the more sense it made. He was even wearing a pair himself!

Excitement swept through my body like a drug

I received my package from GravityDefyer.com and rushed to tear it open like a kid at Christmas. Inside I found the most amazing shoes I had ever seen – different than most running shoes. Sturdy construction. Cool colors. Nice lines… I was holding a miracle of technology. This was the real thing.

GDefy Benefits

- Relieve pain
- Ease joint & spinal pressure
- Reduce fatigue & tiredness
- Be more active
- Have more energy
- Appear taller
- Jump higher, walk and run faster
- Have instant comfort
- Cool your feet & reduce foot odor
- Elevate your performance

I put them on and all I could say was, "WOW!" In minutes I was out the door. I was invincible; tireless in my new Gravity Defyer shoes. It was as if my legs had been replaced with super-powered bionics. What the doctor promised was all correct. No more knee pain. I started to lose weight. At last, I was pain free and filled with energy! I was back in the game. Gravity had no power over me!

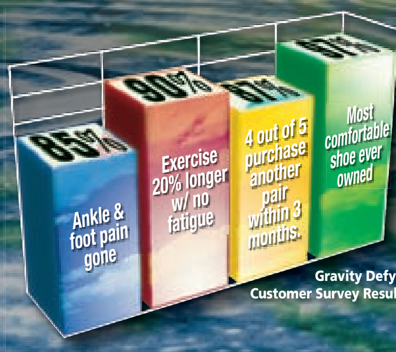
ABSORB SHOCK
Eliminate pain from every step.

Nothing to lose: 30 Day Free Trial*

So, my friend, get back on your feet like I did. Try Gravity Defyer for yourself. You have nothing to lose but your pain.

REBOUND PROPELS YOU FORWARD
Reduce fatigue. Be more active

Tell us your story! Login at Gravitydefyer.com and share your experience.



Gravity Defyer Customer Survey Results

a $129.95 value

MEN (Shown above)
TB902MBL
sizes 7 - 13
Med/Wide and ExtraWide/XXWide Widths

WOMEN (Black on Black)
TB902FBL
sizes 5 - 11
Med/Wide and ExtraWide/XXWide Widths

EXCLUSIVE ONLINE OFFER

TRY TODAY AND PAY IN 30 DAYS* Not available in stores.

Take advantage of this exclusive offer at **www.GravityDefyer.com/MD2ECC3** or by phone, dial **(800) 429-0039** and mention the promotional code below.

Promotional Code: MD2ECC3

*Pay only $14.95 shipping and handling – non-refundable.

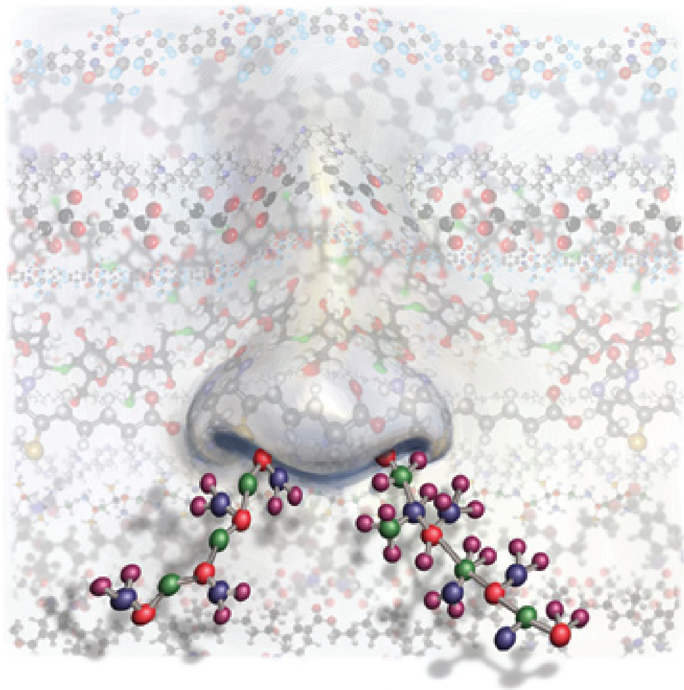
BBB A+

The ongoing search for fundamental farces

Steve Mirsky has been writing the Anti Gravity column since he was a man trapped in the body of a slightly younger man. He also hosts the *Scientific American* podcast Science Talk.

O Mercaptan, My Mercaptan

Some smells always belong, but do not always remain, outside



Friday, February 25, 2011: A date which will live in odiferous infamy. At least at my house.

All seemed well that morning when the rains came. I was warm and dry and didn't need to leave the comfort of home. But that comfort swiftly departed. First, I heard the *glug glug glug*. Then I picked up a whiff both faint and foul. Something was entering the bathroom that should only exit the bathroom—raw sewage was reversing its natural course and fighting its way back into my house.

The whiffs got stronger. Human waste includes some fascinating and fragrant organic compounds. Take skatole. (Please.)

Skatole bears a heavy responsibility for making poo smell phooey. But remember the axiom: it's the dose that makes the poison. Because in low concentrations, according to Wikipedia, skatole "has a flowery smell and is found in several flowers and essential oils," such as orange blossoms and jasmine. It is even used—again, in very small amounts—in perfumes. Think about that when dabbing behind the ears. And Wikipedia notes that cigarette manufacturers add skatole as (*drum roll*) a flavoring ingredient. Just another reason to stop smoking. In addition, waste contains various stinky sulfur compounds, collectively called thiols or mercaptans. They are not your friends.

When sewage is backing up into one's home, the to-do list instantly becomes an un-doo list with only one item: get the plumbers to come immediately. Upon their swift arrival, they unsealed the trap to gain access to the line, which also sent the incoming waste fluid into the subbasement—still bad, but a big improvement. They then sent a camera down the line to examine the problem, performing their version of the closely related diagnostic technique of colonoscopy.

Thus, they found that the clay pipe leading from my house to the city sewer line had been severed. Instead of running slightly downhill, the pipe now pitched slightly skyward. (Technical plumbing lingo: there was a sag in the line.) In the former case, gravity was my friend, gently pulling waste away. But in this new configuration, gravity was a relentless enemy, allowing all things flushed to drift back toward the house. Add the heavy rain, and *glug glug glug*.

By late afternoon I had hired a contractor to tear up the street and replace the busted clay pipe with a cast-iron version this time. I hope to finish paying for this rather costly work before half of the cast iron's alloyed carbon 14 decays. (That's about 5,730 years for those keeping score at home.)

With all this hitting the fan, I was alarmed when my next-door neighbor called to ask me about all the black stuff in front of his house. I told him I'd meet him on our adjoining porches. To my relief, his porch was merely speckled with soot. I looked up the wall and saw that the soot was clearly emerging from the chimney that our furnace exhausts share. "What will we do?" he asked. I explained that we would do nothing because my gas fuel (naturally odorless but laced with mercaptans to make any gas leaks instantly obvious) was unlikely to be producing particulates. He, on the other hand, would have to have his oil-heat system examined for incomplete burning.

With that crisis averted, I turned my attention to tracking the location of the mouse that my cat had caught and was playing Ping-Pong with in the living room. (The mouse being the ball in this metaphor, not the opponent.) The frightened mouse contributed his own tiny measure of mercaptans to the mix.

In the evening, with all situations under semicontrol, I headed out to a local restaurant. As I drove on an unlit, woodsy road, a fluffy, whitish and very still object suddenly appeared in my headlights. Too late—I hit it. And before I could finish the short question—"What was that?"—I knew. Because a flood of fresh, sulfurous mercaptans assaulted my olfaction. My lone comfort was knowing that the poor skunk was already dead when I hit it. I hope the car stops smelling before I pay off the pipe installation. SA

COMMENT ON THIS ARTICLE ONLINE
ScientificAmerican.com/may2011

Illustration by Matt Collins

Actual size is 40.6 mm

Millions are scrambling for the 2011 Silver Eagle...But we're giving it away TODAY at our cost!

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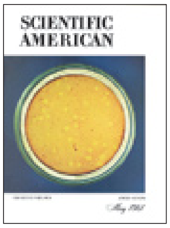
BBB ACCREDITED BUSINESS

Innovation and discovery as chronicled in *Scientific American*



May 1961

Cosmonaut

"On April 12, 1961, Yuri Alekseyevich Gagarin, a citizen of the U.S.S.R., achieved the distinction of being the first man to cross the border between the earth and interplanetary space. The rocket bearing the five-ton spaceship *Vostok* (meaning 'East') was fired aloft at 9:07 A.M. Moscow time. While Gagarin was in orbit he radioed messages such as: 'I am watching the earth. The visibility is good. I feel well and cheerful. The machine is functioning normally.'"

Drummers and Mathematics

"Pushing into the unknown, the mathematician is an explorer who is likely to find what he did not seek and who cannot predict how others will use his discoveries. This particular adventure began when the composer George Perle told me about an elaborate theory of rhythm that had been developed in India more than a thousand years ago. 'While reading about this theory,' he said, 'I learned my one and only Sanskrit word: yamátárájabhánasalagám.' I asked him what it meant. 'It's just a nonsense word invented as a memory aid for Indian drummers.… As you pronounce the word you sweep out all possible triplets of short and long beats.' —Sherman K. Stein"

Stein, currently professor emeritus of mathematics at the University of California, Davis, is also author of Mathematics: The Man-Made Universe. *Full article is available at www.ScientificAmerican.com/may2011/stein*

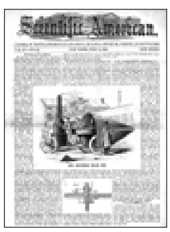
May 1911

Doubts on Airplanes

"In part a flying machine and in part a death trap, the aeroplane has done both more and less than its sudden arrival among the great inventions of the age had promised. This combination of a Chinese kite, an automobile motor, a restaurant fan, balloon rudders, junior bicycle wheels and ski runners, the whole strung together with piano wire and safeguarded with adhesive tape and mammoth rubber bands, sprang from toyland into the world of industry, politics, warfare and finance when two plodding and practical tinkers of genius—self-made engineers from the American school of try, try and try again—proved they could balance and steer it by a twist of its muslin. Now, the world turns a searching glance upon this machine which does so much and fails so treacherously."

Bitter News

"The use of saccharin as an economic sweetening agent in thirty or more food products is to be abandoned. Saccharin has been used to sweeten canned corn, peas, and tomatoes, sarsaparilla, cream soda, and other soft beverages; champagne and liquors. Its use will be unlawful after July 1st. Dr. Wiley, Chief Chemist of the United States Department of Agriculture, says this valuable substance impairs digestion, and should be dispensed only upon a physician's prescription."



May 1861

War Fervor

"The news which vibrated on the electric wires relating the capitulation of Fort Sumter sent a thrill through the heart of the whole people, and the call 'to arms' was heard resounding on every hand. The city appeared almost like a waving forest of flags, the Star Spangled Banner floated from a thousand staffs; it streamed from every window, the bosom of almost every lady and gentleman was adorned with the Red, White and Blue."

Field Guns Advance

"The howitzer was suggested by the experience of the Mexican war, and is designed especially for operations against an enemy having an extensive sea coast and no navy, which can only be attacked either in shallow water or on land. For these operations, boats of light draft are needed and with them, guns combining the greatest possible power with the least possible weight. This combination has been achieved by Captain Dahlgren, in his howitzer, which is now generally adopted in the American navy. The projectiles used in howitzers are shells and canister, to which is now added shrapnels. For operations on shore, the guns are attached to light but strong carriages, such as shown in our illustration."

The Dahlgren gun: mobile artillery is refined, 1861

SCIENTIFIC AMERICAN, VOL. IV, NO. 20; MAY 18, 1861

Famine in Rajasthan

"The news from India is frightful in the extreme; 'famine is devastating the country.' The London *Times* says: 'It is a drought in a land where the sun bakes up the soil almost to the hardness of pottery. Where irrigation works exist the scanty waters will suffice to produce scanty crops, but where there are no such works there is no vegetation to be found. Mr. Edmonstone, the Lieutenant-Governor of the Northwestern Provinces, said that, in a march of twenty miles, there was not a green blade in any direction. Families were fleeing away from the death which threatened them.'"

Exposed

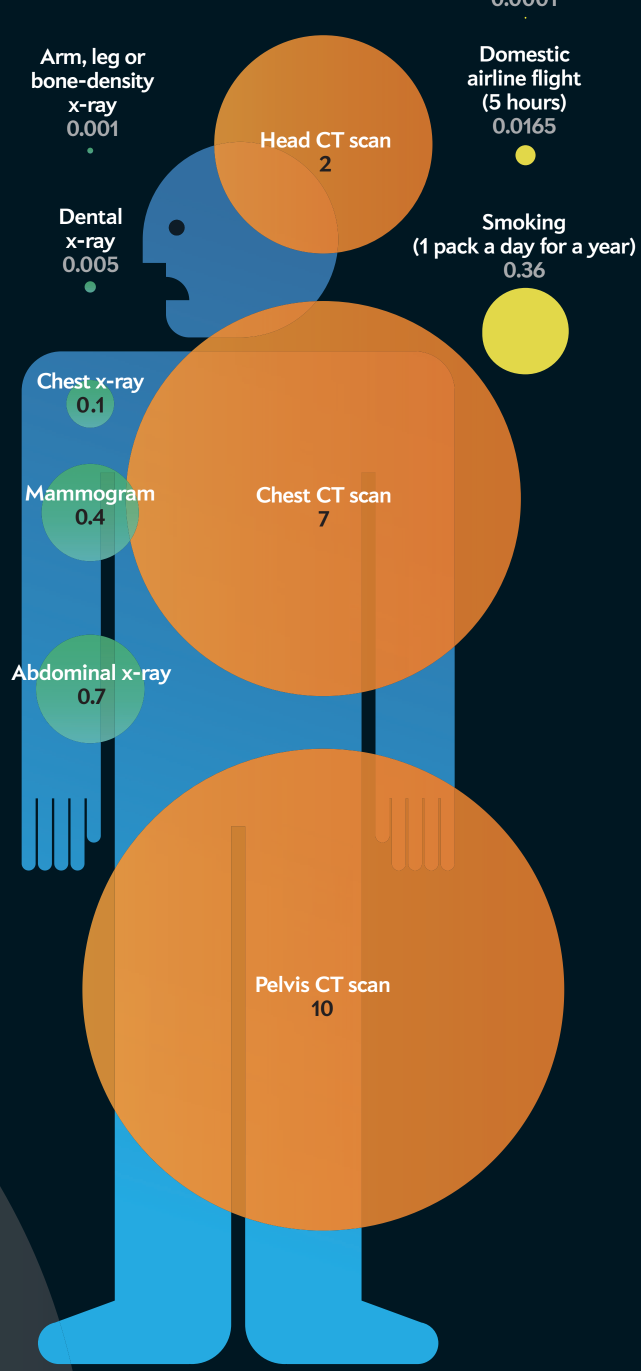
Medical imaging delivers big doses of radiation

Americans are exposed to much more ionizing radiation (the potentially harmful type) than they were 30 years ago. Greater use of medical imaging such as CT scans accounts for almost all the increase. The tests can reveal serious health threats, of course, but they come with risks.

Radiation experts recommend that the public receive less than one millisievert a year beyond natural background radiation (3.1 mSv), not counting medical tests. As shown, common sources such as airport scanners fall far below that recommendation, suggesting that anxiety about certain technologies is unwarranted.

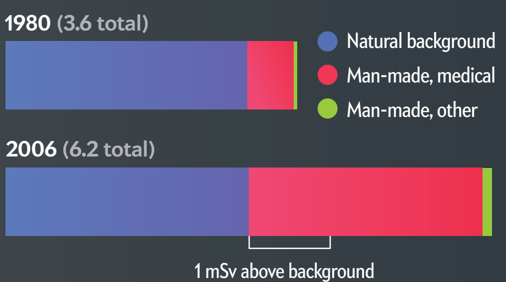
Among medical tests, CT scans are the greatest concern. Studies indicate as many as one third are prescribed unnecessarily. The average exposure for one scan is 7.1 mSv, according to David Schauer, executive director of the National Council on Radiation Protection and Measurements. "There is growing consensus that CT manufacturers should reduce CT scans to less than 1 mSv," he says, adding that at a February meeting, companies indicated new technology could make that possible. —*Mark Fischetti*

Radiation Dose to Entire Body, in millisieverts (mSv)

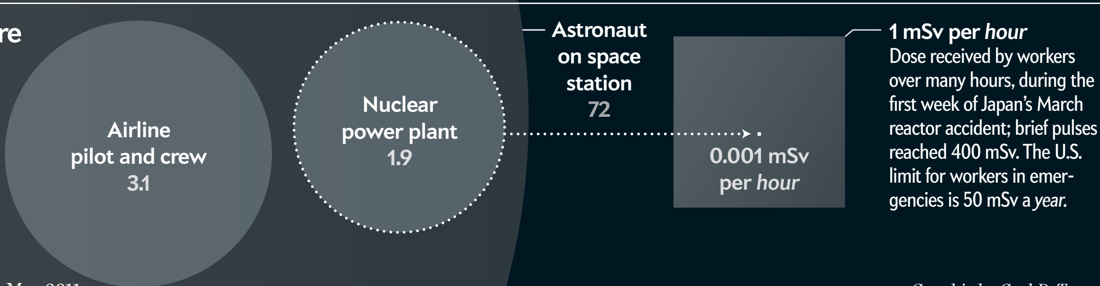


SCIENTIFIC AMERICAN ONLINE
Learn about more sources of radiation at ScientificAmerican.com/may2011/graphic-science

Average Exposure in U.S. (mSv per year)



Worker Exposure (mSv per year above background)



SOURCES: NATIONAL COUNCIL ON RADIATION PROTECTION AND MEASUREMENTS; JAPAN ATOMIC INDUSTRIAL FORUM

Graphic by Carl DeTorres

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