NEUROSCIENCE
Power of the Infant Brain

SUSTAINABILITY
Can Africa's Population Rise to Six Billion?

HEALTH
Taste Receptors Fight Disease

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The Search for Planet X

Is it hidden in the solar system's outer reaches?

FEBRUARY 2016

VOLUME 314, NUMBER 2

SCIENTIFIC AMERICAN

ALEX WILD (*harvester ants*)

ON THE COVER

If the solar system is harboring a hidden planet, it could be a so-called super Earth, a planet up to roughly 10 times more massive than Earth. Such a planet would be too dim and too far to be seen easily by current telescopes, but its gravitational pull could explain some odd behavior among other bodies in the distant solar system. Illustration by Ron Miller.

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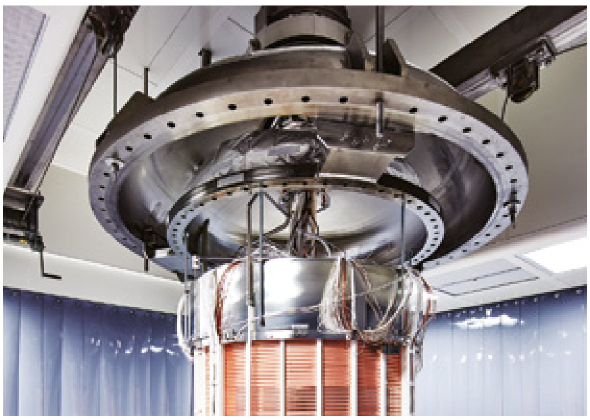

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ON THE WEB

First Footprints on Mars
Scientific American examines NASA's plans to send humans to Mars in the 2030s.
Go to www.ScientificAmerican.com/feb2016/mars

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ENRICO SACCHETTI (*dark matter experiment*)

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Mariette DiChristina is editor in chief of *Scientific American.*
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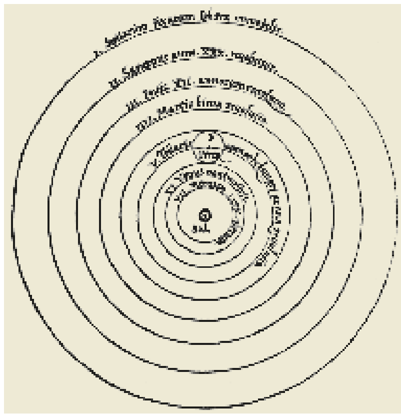
Where Is Planet X?

When we look up at the night sky, it's easy to appreciate how scientists have gained insights from the apparent movements of those twinkling orbs. But it's striking how much of astronomy involves looking for indirect clues to something unseen. As an undergraduate, I reflected on how Neptune revealed itself by subtly shifting the orbit of Uranus. Then Pluto was found when astronomers thought (incorrectly) that something was pulling on Uranus and Neptune.

Now, as staff editor Michael D. Lemonick writes, "Something very odd seems to be going on out beyond Pluto." Could it be another hidden world? In our cover story, "The Search for Planet X," Lemonick describes how "super Earths"—planets with up to roughly 10 times Earth's mass—could be circling the sun beyond our current range of discovery. Today they are too far to be detected, but perhaps future observatories could confirm them, if they exist. Meanwhile we can enjoy the tale of the hunt for the latest icy quarry in the cloud of objects beyond Neptune known as the Kuiper belt. Turn to page 30. And if you enjoy quests for objects in the night sky, after that you might jet to page 70 for "My Life as a Comet Hunter," where David H. Levy describes a "cosmic passion" that's lasted for the past 50 years.



COULD PLANET X EXIST? Although Nicolaus Copernicus's 1543 heliocentric model of the universe was not correct, his concentric rings evoke the widening quest.

In contrast to the expanding universe, Robert Engelman writes, "Earth is a finite place." It's increasingly clear that our species must learn how to live within our means—whether it comes to energy, food, water or any other resource. One way we do that is to use less as a species. And fewer people use fewer resources.

We have been improving on that score, with a global average of 2.5 births per woman, about half the level of six decades ago. But challenges remain where populations are still rising steeply. In "Six Billion in Africa," starting on page 56, Engelman reports that fertility remains high in most of Africa's 54 countries—high enough that by 2100 the continent's 1.2 billion could swell to between three billion and 6.1 billion, adding further challenges to the economies and systems in some of the world's poorest regions. Giving women opportunities and choices over their lives has perhaps the greatest potential. As Engelman says, "The empowerment of women needs no demographic justification," but it is nonetheless a critical factor in helping Africa move toward a more prosperous future. SA

SCIENCE SOURCE

Illustration by Nick Higgins

October 2015

> **"Pharmacists are probably a better choice than physicians to check for drug, food and supplement interactions."**
>
> MIKE M. NAMBA *VIA E-MAIL*

THE FAT SWITCH

In "The Fat Gene," Richard J. Johnson and Peter Andrews argue that ancient apes adjusted to seasonal scarcity by storing fat. What started the seasonal fat accumulation? "Fruit sugar (fructose)" obtained by gorging on fruit flipped "the fat switch" on.

But in the conclusion, the authors say that we should be "cutting way back on our fructose intake—*and getting most of it from fresh fruit*" (emphasis mine). So which is it? Does eating fruit flip the fat switch on, or does it not?

Tim Cliffe
Emmitsburg, Md.

According to the article, our ancestors lost the ability to produce uricase millions of years ago. There are clear downsides to this mutation, but it conveys advantage in times of famine. Is there a similar explanation for our inability to produce ascorbic acid (vitamin C)?

John Pender
Fairbanks, Alaska

THE AUTHORS REPLY: Regarding Cliffe's question, what seems to be a contradiction is really not one. People today mainly get fructose from added sugars, such as table sugar (sucrose) and the high-fructose corn syrup in many sweet beverages and confections. Fruits also contain fructose, but the types of fruit that humans consume have much less fructose and more antioxidants than the very ripe kinds that various animals, such as orangutans, bears and certain types of fish, gorge on to help increase fat stores needed to survive famine. Eating fresh fruit provides us with some of the sweetness that we like but does not give large doses of fructose, and its antioxidants, including vitamin C, can block some of the effects of fructose.

In response to Pender, we have postulated that the mutation that led to the loss of our ability to make vitamin C may have conferred a survival advantage on our ancestors by, again, increasing our ability to store fat. Viewed this way, humans can be considered to have lost two genes—one affecting uricase and the other affecting the ability to produce vitamin C—whose absence helped our ancestors during famine but, in today's world, may be increasing our risk for obesity and diabetes.

BOONDOGGLE FIGHTER

I greatly appreciate your "How Big Is Science?" graphic article, which compares the investment in science in the U.S. with that in other countries and other projects, particularly national security projects. Highlighting the cost of the F-35 Joint Strike Fighter program, the most expensive in the Pentagon's history, brings into stark relief how skewed our national priorities are.

Your readers should know, however, that the cost over the life cycle of the program has been estimated to be $1.4 trillion, more than 3.5 times greater than the Department of Defense's recent program cost estimate of $391.1 billion, which is reported in your graphic. This expense, and the program's troubled history, has made the F-35 the poster child for the Pentagon's mismanagement of taxpayer funds. And unlike many of the programs highlighted in your graphic, it appears that the F-35 will be worse at performing the missions than the legacy platforms it is designed to replace. This is even more evidence that spending on science is dwarfed by the significant costs of our weapons program.

Mandy Smithberger
Director, Center for Defense Information's Straus Military Reform Project, Project On Government Oversight

DRUG INTERACTIONS

Jessica Wapner's article, "Deadly Drug Combinations" [The Science of Health], was excellent but did not mention that pharmacists, such as myself, are probably a better choice than physicians to check for drug, food and supplement interactions. Pharmacies are equipped with drug-interaction software, which pharmacists use when they dispense a prescription. They will alert the prescriber to any potentially dangerous drug interactions so that a more appropriate and safer drug regimen can be selected for the patient.

Mike M. Namba
via e-mail

EVIDENCE-BASED ECONOMICS

"More Evidence, Less Poverty," by Dean Karlan, demonstrated a scientific approach to economic change refreshing to one who, like me, is dumbfounded by the abstruse, casuistic thinking of professional economists. Unfortunately, the author's ego was not constrained by your editors' blue pencil. Others' useful work in this freshly turned and important field might have been mentioned. For example, studies similar to Karlan's, including assessments of microloan programs, have been done by Abhijit Banerjee and Esther Duflo, both at the Massachusetts Institute of Technology.

Further, I long for an article by a political scientist who uses such approaches to demonstrate how civic engagement might be encouraged. In particular, Big Data has transformed "get out the vote" campaigns.

Walter Jonas
via e-mail

EMISSIONS COMPARISONS

"A Greenhouse Gas Surprise," by Mark Fischetti [Graphic Science], illustrates a comparison between nations' total carbon dioxide emissions and their emissions per capita. A somewhat more interesting metric is the amount of greenhouse gases emitted per capita of gross domestic product (GDP). On that scale, France looks very good, the U.S. not extreme (close to the median), and Russia and China pretty bad. How do the French do it? Nuclear power.

VAN SNYDER
via e-mail

BIG NEUROSCIENCE

Stefan Theil's "Trouble in Mind" asks whether the failure of the Human Brain Project was from "poor management" or "something fundamentally wrong with Big Science." A better answer is that although "reverse engineering the human brain" is Big Science, it is also rather low-quality and low-productivity science.

The political climate is such that Big Science programs are attractive, but high-quality projects are not that prevalent. I suggest that such a high-quality project would be the creation of a worldwide initiative to compile and correlate information from the already monstrous neuroscience database. Besides collecting, standardizing, indexing, organizing and summarizing all neuroscience-related data, the project would develop software for finding obscure correlations among a myriad of neuroscience terms, concepts and results, which would likely speed the translational process to improvements in quality of life.

J. WALTER WOODBURY
Professor emeritus of physiology
University of Utah

ERRATUM

In "Hackers at the Wheel" [TechnoFiles, November], David Pogue incorrectly states that remote hacking of a Jeep described in a *Wired* article had involved researchers working on the Jeep's software for three years and that such hacks require physical access to vehicles. The researchers had spent more than a year learning how to hack the Jeep and assert that only remote access would be needed to complete such a hack.

LETTERS TO THE EDITOR

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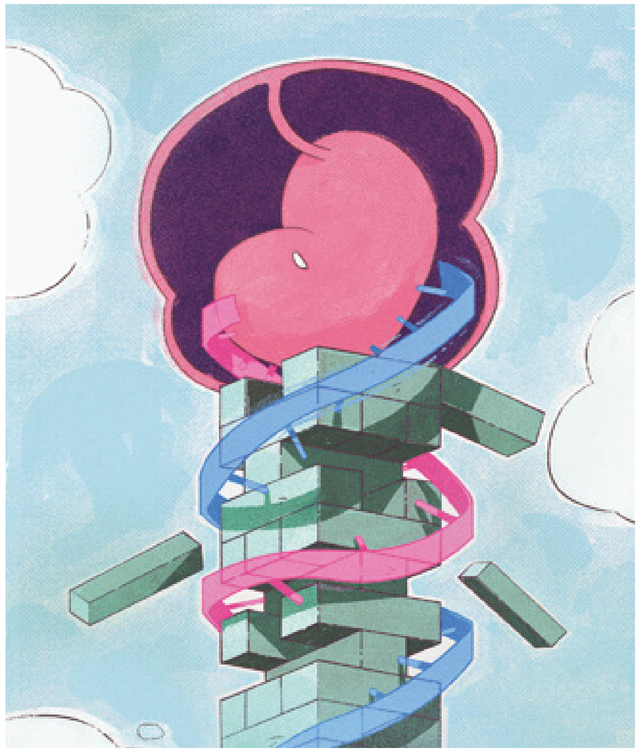
Beware Prenatal Gene Screens

Blood tests are safer for pregnant women but do not tell the whole truth



Expecting a baby often provokes mixed emotions—wonder and amazement but also concern. Will the child be healthy? Happy? Find his or her spot in the world? Several prenatal blood tests are now available that attempt to ease some of the anxiety—at least about health. By analyzing trace amounts of fetal DNA in a pregnant woman's bloodstream, these tests (which go by such names as Harmony, MaterniT21 PLUS and verifi) can identify various genetic anomalies up to six months before birth. Whether or not parents to be take advantage of these laboratory measures is, of course, up to them. But results from screening tests can be misleading, and industry and federal regulators are not doing enough to ensure that people get all the information they need.

At present, the tests detect major abnormalities—such as three copies of the 21st, 18th or 13th chromosome, which lead, respectively, to Down, Edwards and Patau syndrome. These measures are a definite safety improvement over earlier procedures to check the genes of the unborn. Previously such chromosomal abnormalities could be detected prenatally only by invasive tests, such as amniocentesis, which carry a small risk of triggering a miscarriage.

The new screens were originally offered to women older than 35 years, who are at a higher risk of delivering babies with Down syndrome or other genetic maladies. But now companies are marketing such tests to women with low-risk pregnancies as well. Last November a market research firm reported that the tests accounted for $563.4 million worth of sales in 2014—a figure that is expected to quadruple by 2022.

Federal regulations have not caught up with the advancing technology, however. Under current rules, such gene screens are considered lab tests, which, unlike new drugs, do not have to show they offer clinically meaningful benefits. Instead manufacturers only need to demonstrate that their tests generate results within certain statistically acceptable limits of error.

This standard made more sense in the days when blood tests looked primarily for individual compounds, such as sugar molecules or hormones. Gene tests are different: they take a lot more interpretation and analysis to determine if a suspicious result indicates a true genetic aberration or merely a benign variation.

For one thing, the amount of fetal DNA found in the maternal bloodstream is minute and must be copied many times to generate enough material to test. The amplification process, among other things, may lead to double counting mistakes that give the false impression of an extra 21st chromosome, for example, where none exists. A second source of uncertainty stems from the fact that the new genetic tests are actually screening tests, which, by definition, cast a broad net that includes many more false-positive results than more specialized diagnostic procedures that are typically more accurate.

Ignoring this distinction can lead to serious problems. If a screening test on 1,000 people correctly identified 19 out of 20 true cases of a genetic problem, it would have what statisticians call a sensitivity rate of 95 percent. That sounds pretty good, but that same test might also yield 10 false positives—10 other people in the group for whom the test incorrectly suggested a problem. The sensitivity rate would still be 95 percent because the test caught most of the true positives. But just over 65 percent of all the positive results—19 out of 29—were actually correct.

It is this last ratio—what statisticians called the positive predictive value—that tells you how much faith you should really have in a particular test result. And yet most gene-screening companies do not provide the positive predictive values for their tests. Instead they tout their tests' sensitivity rate, which can mislead patients and even their physicians. Problems with prediction are why anyone who receives a positive result from a screening test should follow it up with a more precise diagnostic exam.

The U.S. Food and Drug Administration also needs to follow up on these tests. It should accelerate efforts to change the rules so that the makers of gene screens give more clinically relevant information, such as predictive values. The companies that offer noninvasive prenatal screening should do more to educate all of us about a test's potential drawbacks. And expectant parents should think carefully about whether they want to undergo these screenings in the first place, particularly because new blood tests that supposedly provide a glimpse into the entire fetal genome—including possible predispositions to heart disease, cancer or diabetes—are just around the corner. SA

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Illustration by Justin Volz


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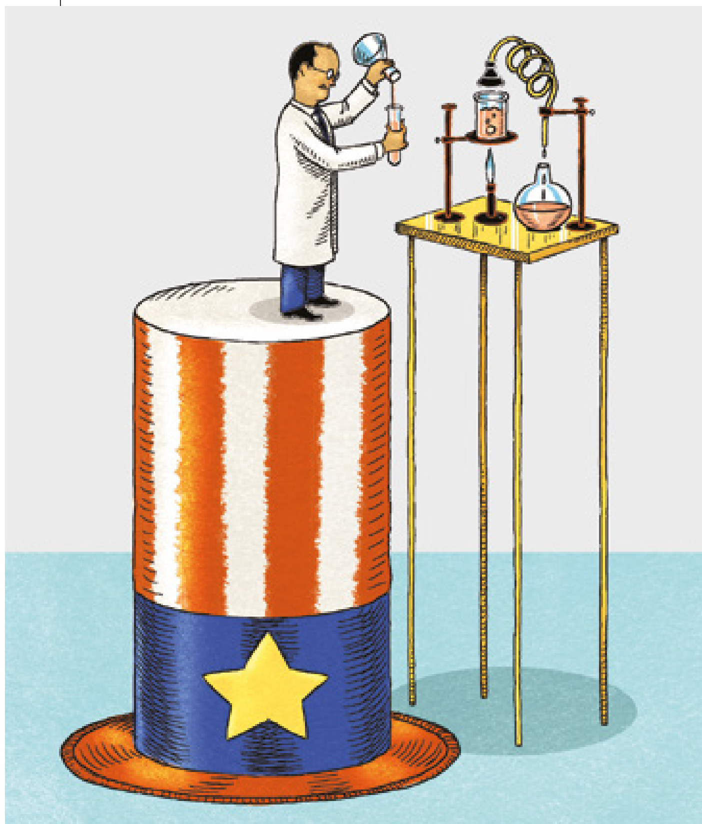
Nathan Myhrvold is founder and CEO of Intellectual Ventures in Bellevue, Wash. He previously worked for Microsoft as chief technology officer and founded Microsoft Research.

Even Genius Needs a Benefactor

Without government resources, basic science will grind to a halt

By Nathan Myhrvold



On December 2, 2015, the centennial anniversary of the publication of Einstein's general theory of relativity, science fans everywhere reflected on this amazing act of genius. But the theory was not born, fully formed, in some eureka moment. Albert Einstein chipped away at it for years. He was finally driven to complete it by a fierce (though collegial) rivalry with mathematician David Hilbert [see "How Einstein Reinvented Reality," by Walter Isaacson; Scientific American, September 2015].

Examine the detailed history of almost any iconic scientific discovery or technological invention—the lightbulb, the transistor, DNA, even the Internet—and you'll find that the famous names credited with the breakthrough were only a few steps ahead of a pack of competitors. Recently some writers and elected officials have used this phenomenon, called parallel innovation, to argue against the public financing of basic research.

In his new book, *The Evolution of Everything* (Harper, 2015), for example, British science writer Matt Ridley claims that government just gets in the way of the natural evolution of science and invention. Many in the U.S. Congress agree. We spend too much taxpayer money on science, some politicians say. Government should leave it to companies to finance the research they need.

These arguments are dangerously wrong. Without government support, most basic scientific research will never happen. This is most clearly true for the kind of pure research that has delivered enormous prestige and great intellectual benefits but no profits, such as the work that brought us the Higgs boson, or the understanding that a supermassive black hole sits at the center of the Milky Way, or the discovery of methane seas on the surface of Saturn's moon Titan. Company research laboratories used to do this kind of work: experimental evidence for the big bang was discovered at AT&T's Bell Labs, resulting in a Nobel Prize. Now those days are gone.

Even in applied fields, such as materials science and computer science, companies now understand that basic research is a form of charity—so they avoid it. Scientists at Bell Labs created the transistor, but that invention earned billions for Intel (and Microsoft). Engineers at Xerox PARC invented the modern graphical user interface, although Apple (and Microsoft) profited the most. IBM researchers pioneered the use of giant magnetoresistance to boost hard-disk capacity but soon lost the disk-drive business to Seagate and Western Digital.

When I created Microsoft Research, one of the largest industrial research labs founded in a generation, Bill Gates and I were very clear that basic research was not our mission. We knew that unless our researchers focused narrowly on innovations we could turn into revenues quickly, we wouldn't be able to justify the R&D budget to our investors. The business logic at work here has not changed. Those who believe profit-driven companies will altruistically pay for basic science that has wide-ranging benefits—but mostly to others and not for a generation—are naive.

If government were to leave it to the private sector to pay for basic research, most science would come to a screeching halt. What research survived would be done largely in secret, for fear of handing the next big thing to a rival. In that situation, Einstein might never have felt the need to finish his greatest work.

Einsteins are few and far between. But we don't have to wait for a rare genius as long as we stoke the competitive instincts of the smartest people around and persuade them to share their discoveries, in exchange for a shot at glory and riches. SA

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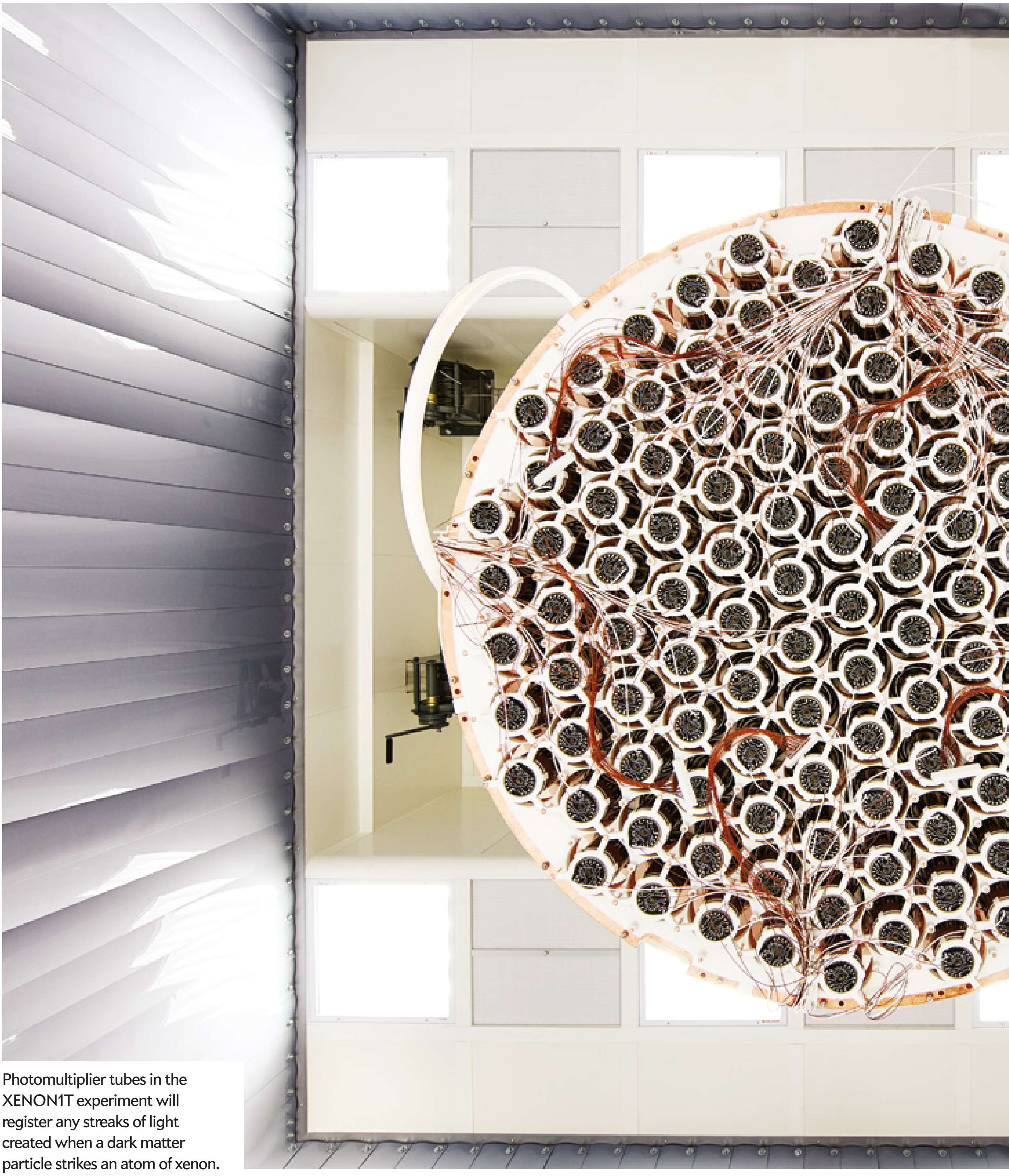
Illustration by Wesley Bedrosian

ADVANCES



Photomultiplier tubes in the XENON1T experiment will register any streaks of light created when a dark matter particle strikes an atom of xenon.

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INSIDE

PHYSICS

Last Call: Will WIMPs Show Their Faces?

New search for dark matter aims to succeed where others have failed

It's now or never for physicists' favorite explanation of dark matter, the invisible material that seems to pervade the universe. The largest, most sensitive search yet for the particles many physicists think make up dark matter—weakly interacting massive particles (WIMPs)—will begin in March at the XENON1T experiment at the Gran Sasso National Laboratory in Italy.

The project is the latest in a line of detectors that date back as early as the 1980s but have all failed so far to find dark matter. If the elusive particles go unfound in the next few years at XENON1T, physicists may have to abandon the leading theory and search for more exotic explanations. "Our best models are within reach of XENON1T," says Rafael Lang, a physicist at Purdue University who works on the experiment. "If we don't see it, that means our ideas are completely wrong, and we really have to go back to the drawing board."

Technicians prepare the experiment's Time Projection Chamber, which houses xenon and is ringed by copper to ensure a uniform magnetic field.

WIMPs are a prediction of superstring theory. This extension of the Standard Model of particle physics proposes the existence of partner particles for all the known fundamental bits of matter in the universe. WIMPs would be the lightest of these partners, and physicists favor them because the theory naturally predicts just about the amount of dark matter that experts know must exist because of its gravitational pull. (Dark matter represents an estimated 84 percent of all matter in the cosmos.) Many versions of WIMPs have already been ruled out because previous searches for them turned up nothing, but investigators are still hopeful that one of the remaining possibilities will show up.

Buried in a cave 1,400 meters underground, XENON1T houses a large cylindrical vat filled with 3,500 kilograms of liquid xenon. The substance naturally gives off light when its atoms are disturbed; scientists are aiming to catch the rare occasion when a dark matter particle collides with a xenon nucleus, an impact that should leave a unique energy signal. Although dark matter is thought to be ubiquitous—roughly 100,000 dark particles fly through every square centimeter of space each second—it almost never interacts with regular matter and generally makes its presence known only through gravity. After the planned two-year search at XENON1T, the detection of just 10 particles that appear to match dark matter's predicted properties would be enough to claim a discovery.

The $15-million project, sponsored by a collaboration among 10 different countries, follows a previous iteration of the experiment that was 25 times smaller. The new XENON's larger collecting volume, as well as improved shielding to block other particles that might masquerade as dark matter, should allow it to surpass the earlier experiment's level of sensitivity within two days of turning on. It should also overtake the current leading dark matter experiment, the 370-kilogram Large Underground Xenon experiment (LUX) in South Dakota, within weeks. "I would not at all be surprised if XENON1T were able to make a discovery that had just barely escaped the generations of experiments that came before it," says Tim Tait, a theorist at the University of California, Irvine, who is not involved in the experiments.

Meanwhile WIMPs could also show up any day now at the Large Hadron Collider near Geneva, where protons crash into one another at near the speed of light to give rise to new particles. The accelerator began a second run last year at almost twice the energy with which it turned on in 2009 and now should be powerful enough to create roughly the same range of WIMPs that might be detectable at XENON1T.

And if in the next few years, neither of them sees a hint of the particles, the time may come for theorists to move on to another explanation for dark matter. "On one hand, we know it exists, but on the other hand, we know very little about it, so it's very easy to theorize about possibilities," Tait says. "If we don't see it, that tells us the dark matter has turned out to be more weird and wonderful than we had originally guessed it might be."

—*Clara Moskowitz*

HEALTH

Talk Therapy

Research reveals the diagnostic potential of patient chatter

Future doctors may ask us to say more than "Ahhh." Several groups of neuroscientists, psychiatrists and computer scientists are now investigating the extent to which patients' language use can provide diagnostic clues—before a single laboratory test is run. Increased computing power and new methods to measure the relation between behavior and brain activity have advanced such efforts. And although tests based on the spoken word may not be as accurate as gene sequencing or MRI scans, for diseases lacking clear biological indicators, language mining could help fill the gap. —*Anne Pycha*

PSYCHOSIS

Psychiatrists at Columbia University interviewed 34 young adults at risk for psychosis, a common sign of schizophrenia that includes delusions and hallucinations. Two and a half years later five of the subjects had developed psychosis, and the remaining 29 remained free of the disorder. A specially designed algorithm combed the initial interviews collectively to look for language features that distinguished the two groups and found that psychosis correlated with shorter sentences, loss of flow in meaning from one sentence to the next and less frequent use of the words "that," "what" and "which." When later tested on each individual interview, the computer program predicted who did and who did not develop psychosis with 100 percent accuracy. The results were recently published in *Schizophrenia,* and a second round of testing with another group of at-risk subjects is now under way.

PARKINSON'S DISEASE

Twenty-seven subjects in a study at Favaloro University in Argentina listened to recorded sentences containing verbs associated with specific hand shapes (such as "applaud" or "punch"). As soon as they understood the sentence, participants pressed a button while keeping both hands in either a flat or clenched-fist position. Healthy subjects responded more quickly

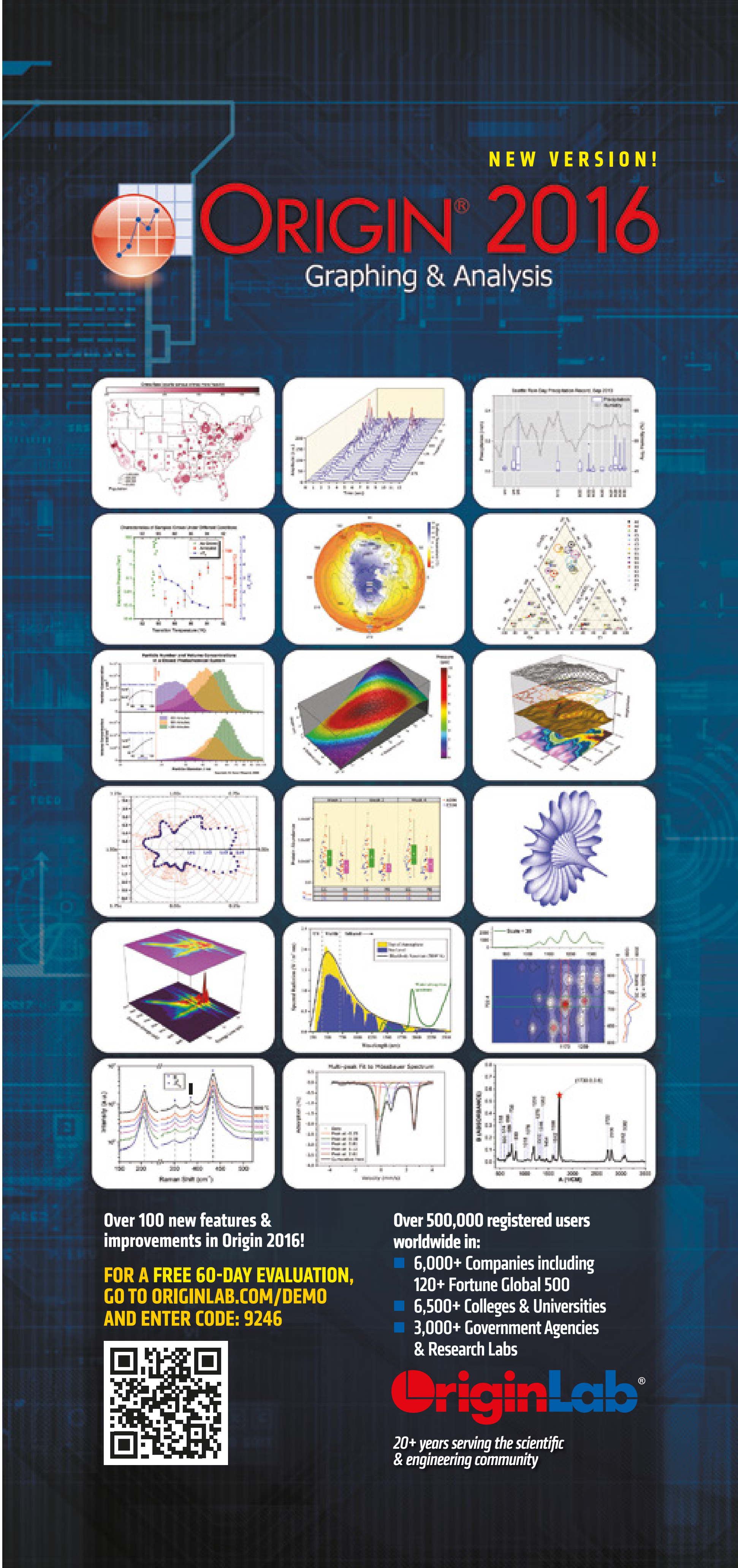
PRECEDING PAGES AND THIS PAGE: ENRICO SACCHETTI

when the verb and hand shape were compatible (flat for “applaud,” clenched fist for “punch”) compared with when they were incompatible. Subjects with early-stage Parkinson’s disease, however, showed no difference in their reaction times. Such disconnects could serve as an early sign of the disease, before the onset of severe problems. Now the researchers are conducting a similar study with subjects who currently are healthy but carry a genetic mutation associated with Parkinson’s.

AMYOTROPHIC LATERAL SCLEROSIS (ALS)

ALS is typically characterized as a movement disorder, which can lead some patients to speak unclearly because of weak muscles. A new study led by Sharon Ash at the University of Pennsylvania shows that the disease may also disrupt grammar usage. Forty-five subjects were asked to narrate the events in a series of 24 pictures, using their own words. ALS patients produced more incomplete sentences (“And he’s angry ’cause it—”), more missing determiners (“Owl flew around”) and more errors in verb tense (“And the deer push him off a cliff”), compared with healthy controls. MRI scans revealed that people who made more grammatical errors also showed more deterioration of brain regions associated with language, suggesting that grammar analysis may be a relatively simple way to assess disease onset and severity. In an ongoing follow-up study, Ash and her colleagues are analyzing patients’ shorter utterances, prompted by a single picture.

Illustration by Thomas Fuchs



THE SENSES

The Ear as Tape Measure

Humans use sight—and hearing—to approximate distance

The experience of seeing a lightning bolt before hearing its associated thunder some seconds later provides a fairly obvious example of the differential speeds of light and sound. But most intervals between linked visual and auditory stimuli are so brief as to be imperceptible. A new study has found that we can glean distance information from these minimally discrepant arrival times nonetheless.

In a pair of experiments at the University of Rochester, 12 subjects were shown projected clusters of dots. When a sound was played about 40 or 60 milliseconds after the dots appeared (too short to be detected consciously), participants judged the clusters to be farther away than clusters with simultaneous or preceding sounds. Philip Jaekl, the lead author of the study and a postdoctoral fellow in cognitive neuroscience, says it makes sense that the brain would use all available sensory information for calculating distance. "Distance is something that's very difficult to compute," he explains. The study was recently published in the journal *PLOS ONE.*

Aaron Seitz, a professor of psychology and neuroscience at the University of California, Riverside, who was not involved in the work, says the results may be useful clinically, such as by helping people with amblyopia (lazy eye) improve their performance when training to see with both eyes. And there might be other practical applications, including making virtual-reality environments more realistic. "Adding in a delay," says Nick Whiting, a VR engineer for Epic Games, "can be another technique in our repertoire in creating believable experiences." —*Geoffrey Giller*

BY THE NUMBERS

343
METERS/SECOND
Speed of sound in dry air at 68 degrees Fahrenheit.

299,792,458
METERS/SECOND
Speed of light in a vacuum.

DON GRALL *Getty Images* (*lightning*); SOURCES: HYPERPHYSICS *http://hyperphysics.phy-astr.gsu.edu/hbase/sound/souspe3.html* (*top stat*); NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY REFERENCE ON CONSTANTS, UNITS, AND UNCERTAINTY *http://physics.nist.gov/cgi-bin/cuu/Value?c* (*bottom stat*)

COMMENT AT ScientificAmerican.com/feb2016

Fishers, also known as fisher cats, lead solitary lives.

CONSERVATION

Poison Pot

Rat bait at marijuana farms is needlessly killing larger mammals whose numbers are dwindling

The Pacific fisher, a house-cat-size member of the weasel family, lives in some of California's remotest forests. Trapping and logging going back to the 1800s had reduced the fisher's U.S. population to a few thousand at most. Those threats waned, but a new one has emerged: pesticides used at illegal marijuana farms. Thousands of these sites have popped up statewide, particularly in national forests, despite the potential to grow legally under California's 1996 medical marijuana law.

Mourad W. Gabriel, executive director of the nonprofit Integral Ecology Research Center, first suspected a link in 2011 between a rash of fisher deaths and California cannabis. Necropsies already had shown that rat poisons were killing fishers, but the source of the chemicals was unknown. At a conference for wildlife professionals that year, a law-enforcement officer mentioned to him that agents often came across these poisons at so-called trespass grow sites on public and tribal land. The compounds had been applied in ways that violated vermin-control regulations with which conventional farmers are expected to comply. Although fishers are not the intended target, they—along with black bears, gray foxes and a wide array of other animals—bleed out internally if they consume the bait or poisoned rodents.

So Gabriel and his friend Mark Higley, a wildlife biologist at the Hoopa Tribal Forestry Department, began tagging along on raids, sometimes entering an illegal grow site while dangling, commando-style, from a rope attached to a police helicopter. Almost without fail, the pair encountered the chemicals—some still in their packages, others strewn about haphazardly—known to be killing fishers, including some banned for use in the U.S. An exhaustive search revealed no one else was dumping pesticides that deep in the woods. The team had found its culprit.

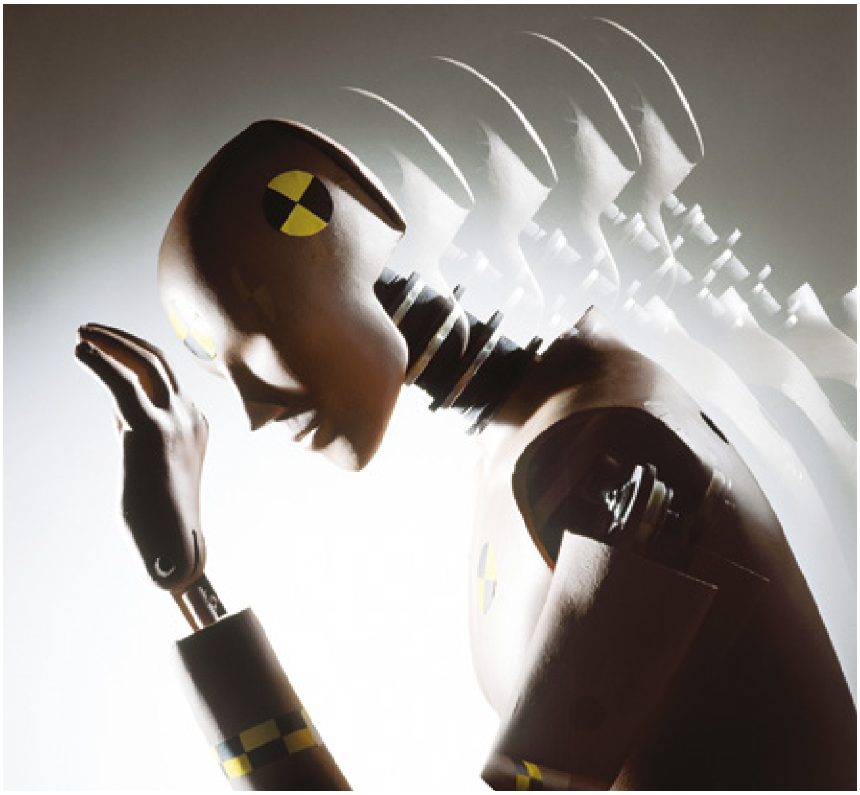
The researchers detailed the problem last November in *PLOS ONE.* Of 129 radio-collared Pacific fishers for which the cause of mortality could be determined over an eight-year span, poison at illegal pot farms was found to have killed 13. Such a loss is devastating for a population that has been proposed for listing under the Endangered Species Act. To make matters worse, fully 85 percent of 101 fishers tested from 2012 to 2014 showed exposure to rodenticides, meaning even those that did not die outright were potentially sickened, which could impair their ability to hunt, reproduce or elude predators.

Meanwhile trespass growers also divert billions of gallons of freshwater and leave behind mountains of garbage, ranging from propane tanks and fertilizer to candy wrappers and car batteries, on land where no mechanism for cleanup exists. "The places are just disasters," says Craig Thompson, a wildlife ecologist at the U.S. Forest Service and lead author of a 2014 paper showing that proximity to illegal cultivation sites affects fisher mortality rates. "It's stunning the amount of destruction that can be packed into a two-acre plot."

California is by far the country's leading producer of marijuana; the U.S. Drug Enforcement Administration reports that of the 3.9 million illegal outdoor plants eradicated nationwide in 2014, 62 percent grew in the Golden State. "It's everywhere," says Capt. Nathaniel Arnold of the California Department of Fish and Wildlife. He points out that armed suspects occasionally engage in shoot-outs with law enforcement or threaten civilians who stumble on them accidentally. Such incidents can discourage wildlife researchers from getting involved in issues that impinge on the contemporary culture wars around marijuana. Yet, as Higley points out, conservationists do not condemn marijuana per se. "You're not supposed to be doing agriculture out in the woods," he says. "It would not matter what they were growing out there."

—*Jesse Greenspan*

JOEL SARTORE *Getty Images*



STEVE HATHAWAY *Getty Images*

TECHNOLOGY

The New Crash Test Dummy

A virtual model could improve vehicle safety features

You can learn a lot from a dummy, but the auto industry's standardized—and federally mandated—crash test dummies are left wanting. Biological engineers often find it difficult to use them to model body blows coming from certain directions or to predict trauma to areas such as the lumbar spine and abdomen. To make a more accurate, responsive model of human injury, nearly two dozen automakers and research institutes have set out together to build a digital complement: an elaborate, 3-D computer model depicting bone, tissue and internal organs from head to toe. To date, the group, known as the Global

Human Body Models Consortium (GHBMC), has created a 173-pound adult model and continues to make updates for a broader range of body types and scenarios. The effort comes at a time when U.S. traffic safety administrators report an 8.1 percent increase in traffic fatalities for the first six months of 2015, compared with 2014 data from the same period—the largest increase year over year since 1977.

—*Peter Andrey Smith*

ALL SHAPES AND SIZES

Most automobile safety features were designed with the average adult male in mind, which has left children in particular not as well-protected. From an engineering standpoint, the prepubescent body has different mechanical properties, so one goal of the consortium is to make anthropomorphic details in the model account for kid-sized bodies, as well as other variations in sex and age. A similar model for 10-year-olds is already helping postdoctoral researchers Anil Kalra and Ming Shen of Wayne State University develop new bumpers that make young pedestrians struck by vehicles more likely to land on their hands and feet than on their head.

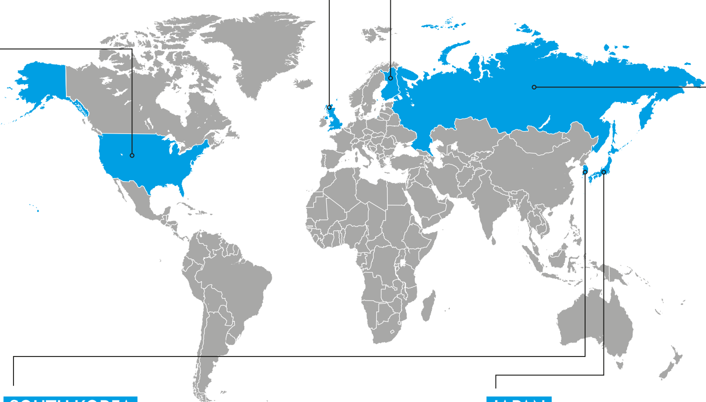
INJURY PREDICTION

In the event of a crash, General Motors vehicles with the OnStar telematics system already collect collision data, including force and direction of impact, to calculate the likelihood of severe injury to passengers. The system then sends this prediction to emergency responders. J. T. Wang, an engineer at GM and a lead technical adviser to the GHBMC, speculates that the virtual-body model may eventually run fast enough to create real-time simulations that enable vehicles with such systems to give a more specific picture of the crash scene. “Even before the emergency team arrives at the site, we may be able to predict the *kind* of injuries,” Wang says. This information could also provide paramedics with crucial clues about the underlying conditions afflicting crash victims who are found unconscious.

DRIVERLESS CARS

The anticipated widespread elimination of human drivers (and hence human error) will not likely eliminate injuries. As such, Jingwen Hu, a research scientist at the University of Michigan’s Transportation Research Institute, suspects the GHBMC models will be instrumental in fine-tuning the safety features of autonomous cars, which have different operating mechanisms than cars today and may sport unconventional seating configurations. For instance, in a recent paper funded by Ford Motor Company, Hu found that the braking of vehicles with driver-assist technology just before a potential collision tends to alter a front-seat rider’s posture. As a result, the skull tilts forward—which could increase the risk of head injuries. The models could also soon help engineers reevaluate the operation of seat belts and air bags in this new context.

IN THE NEWS
Quick Hits



U.K.
Officers at U.K. ports impounded thousands of hoverboards after safety tests by several retailers revealed the motorized boards were at risk of exploding or bursting into flames. New York City, meanwhile, has already deemed the devices illegal because they cannot be registered as motor vehicles.

FINLAND
The country has become the first to approve construction of a dedicated facility to house the highly radioactive material produced by nuclear power plants. Other countries store spent nuclear fuel in temporary facilities.

U.S.
The American Medical Association called for a ban on drug ads that directly target the general population, such as those broadcast on television. The group argues that these promotions result in higher health care costs because they boost demand for expensive treatments. The U.S. is one of only two countries that allow direct-to-consumer ads from pharmaceutical companies.

RUSSIA
A fossilized tooth discovered in a Siberian cave yielded DNA from Denisovans, members of a *Homo* species that is thought to have lived alongside humans and Neandertals. The finding pushes back the oldest known evidence for the Denisovans by 60,000 years.

SOUTH KOREA
Researchers at the Electronics and Telecommunications Research Institute announced that they produced the first 360-degree color hologram, in the form of a floating Rubik's Cube.

JAPAN
Japanese electronics company Epson will release an in-office paper-recycling machine this year. The system, which is the size of a walk-in closet, breaks down wastepaper and produces new white sheets at a rate of 14 sheets per minute.

For more details, visit www.ScientificAmerican.com/feb2016/advances

COMMENT AT ScientificAmerican.com/feb2016

ASTRONOMY

Space Jellies

Rare, enchanting systems may result when clusters of galaxies collide

Located 220 million light-years away, this jellyfish galaxy migrates toward one o'clock.

COURTESY OF HUBBLE SPACE TELESCOPE, NASA, ESA AND HUBBLE HERITAGE TEAM (STScI/AURA); ACKNOWLEDGMENT: M. SUN *University of Alabama in Huntsville*

Jellyfish appear to swim through the heavens just as they do through the seas. In recent years astronomers have spotted spiral galaxies that resemble the exotic creatures, trailing blue tendrils of gas and young stars. Now a search for more of these intriguing galaxies has yielded insights into their origin.

To locate celestial jellyfish, astronomers Conor McPartland and Harald Ebeling of the University of Hawaii at Manoa and their colleagues searched within 63 galaxy clusters, which harbor numerous large galaxies embedded in torrid gas. The team already knew that "jellyfish" arise when a luckless spiral galaxy falls into a galaxy cluster and the hot gas there strips away the spiral's gas, yielding streamers that spawn new stars. The brightest young stars shine blue, lending color to the jellyfish's tentacles. In total, nine previously undiscovered jellyfish galaxies were found.

All was not as expected, however. "We realized there's something funny here," Ebeling says. "These galaxies are not moving toward the centers of the clusters." Because of each cluster's gravitational pull, the jellyfish should have been heading into the cluster cores—a direction signaled by the trailing tentacles. Yet the galaxies were moving every which way. Similarly, the jellies' whereabouts were strange: they all dwelled in the cluster outskirts.

These observations suggest jellyfish creation also requires a cluster-cluster collision, during which speeding galaxies from one cluster smash through the hot gas of the other. In the ensuing chaos, galaxies would dart through space in all directions, as seen in the new data set. The research was published in January in *Monthly Notices of the Royal Astronomical Society.*

To confirm this idea, the researchers now plan to examine the gas in clusters harboring jellyfish galaxies. Cluster gas is so hot that it emits x-rays, but in the collision scenario, the gas in jellyfish-bearing clusters should be especially hot where the clusters smack into one another. If x-ray observations verify this scenario, galactic jellyfish must be victims of violence. Born in the aftermath of enormous collisions, they are destined to lose all their gas and metamorphose into elliptical galaxies, bland objects that lack gas and thus the beauty of star-spawning spiral arms.

—*Ken Croswell*

MATERIALS SCIENCE

Elemental Urgency

Most metals currently lack substitutes

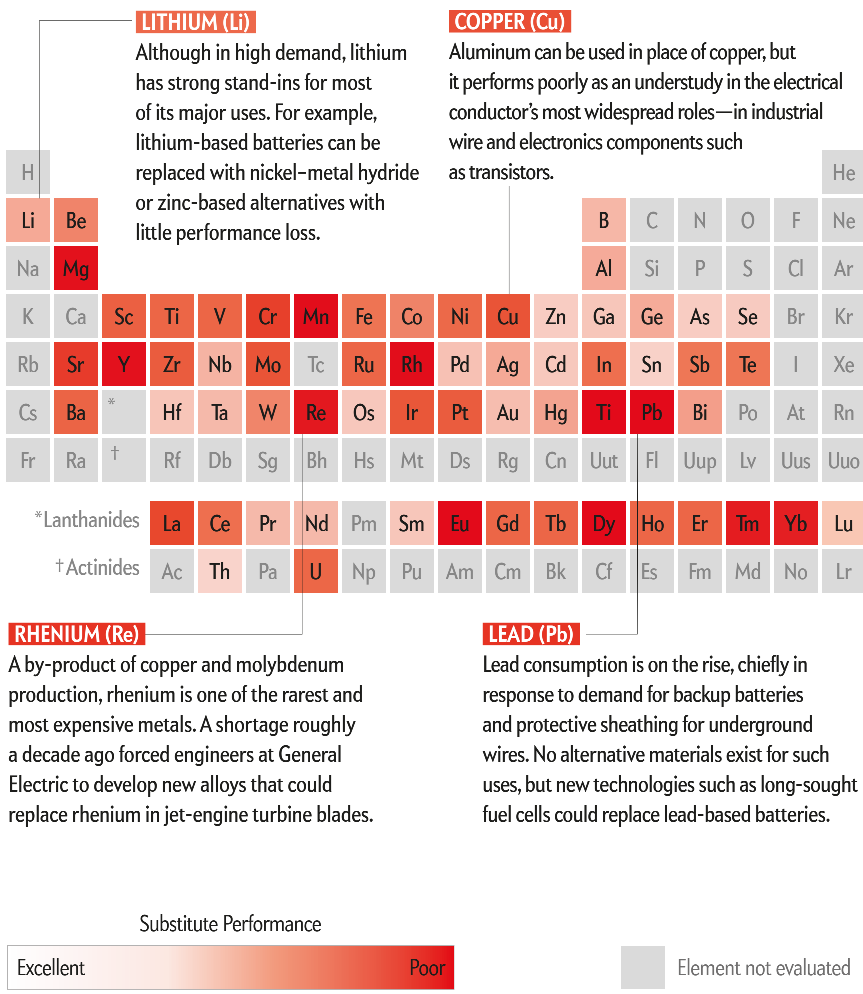
Half a century ago only a handful of materials were in widespread use for consumer and industrial products—wood, iron and brick, to name a few of the most prominent ones. Today a single computer chip contains more than 60 elements, ranging from tungsten to ytterbium. Contemporary technology's reliance on such diverse resources, particularly metals, piqued the interest of Thomas Graedel, an environmental scientist at Yale University. With increasing demand for these elements, are replacements available if a shortage occurs?

In most cases, no. In fact, strong substitutes exist for none of the examined 62 metals or metalloids on the periodic table in all their uses, Graedel and his colleagues found after a comprehensive analysis of the elements' properties, life cycles and applications. And inadequate or nonexistent alternatives plagued a dozen metals when it came to their major uses. Replacements in these cases invariably would lead to degraded performance.

There may be a silver lining to situational scarcities, however, Graedel says. They should inspire engineers to design completely novel, transformative materials.

—Jennifer Hackett

The Periodic Table of Substitute Availability



SOURCE: "ON THE MATERIALS BASIS OF MODERN SOCIETY," BY T. E. GRAEDEL ET AL., IN *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES USA*, VOL. 112, NO. 20; MAY 19, 2015

Illustration by Daisy Chung

ANIMAL BEHAVIOR

When Love Wins

One avian species chooses quality time over food

Like most birds, the great tit is (mostly) monogamous. Every winter pairs of the stunning yellow-breasted songbirds (*above*) reunite for the upcoming breeding season and spend the bulk of their time together—staking out territory, building nests and even foraging. The strength of their bond is palpable, but what would happen if the birds were forced to choose between love and food?

To find out, University of Oxford zoologist Josh A. Firth and his colleagues arranged a set of feeders in a forest near the English countryside. Some of those feeders were set to open only for birds that had been tagged with odd-numbered microchips; others allowed access only to those tagged with even numbers. Thus, pairs with matching assignments could open the same feeders and feast on sunflower seeds together. Mismatched couples, on the other hand, were forced to dine at different venues.

Over the course of three months the researchers monitored 17 couples, including seven odd-plus-even pairs that could not eat at the same feeders. They found that birds from those mismatched pairs visited inaccessible feeders nearly four times as often as those from matched pairs, suggesting that mates were sticking together even if it meant one of them lost out on a meal. The results were published in December in *Current Biology.*

Great tit couples may remain side by side even when one of them is hungry because they will need each other later on. "The pair bond is vital for great tits," Firth says. "Single parents cannot cope with the demands of raising a brood alone. Their only hope for success depends on having a supportive and reliable partner."

Andrew King, a behavioral ecologist at Swansea University in Wales, says that these findings mirror observations in a wide variety of animals, ranging from primates to fish. "Getting less food and foraging with a 'friend' may still be better than getting more food and foraging [alone]," he says. In fact, many of the thwarted birds in the experiment eventually learned to scrounge quickly from their partner's food, taking advantage of a two-second window before the feeders locked back up.

—*Jason G. Goldman*

BUITEN-BEELD *Alamy*

David Pogue is the anchor columnist for Yahoo Tech and host of several *NOVA* miniseries on PBS.

Get Out the iVote

When will we bring our democratic process into the 21st century?

By David Pogue

Sooner or later everything seems to go online. Newspapers. TV. Radio. Shopping. Banking. Dating.

But it's much harder to drag *voting* out of the paper era. In the 2012 presidential election, more than half of Americans who voted cast paper ballots—0 percent voted with their smartphones.

Why isn't Internet voting here yet?

Imagine the advantages! There'd be no ambiguity, no hanging chads or errant marks. We'd get the totals instantly.

And think how online voting would boost participation! If most people didn't actually have to *go* somewhere to vote, you'd have a much better turnout than the measly 61.8 percent who bothered in the 2012 election.

You'd also cut costs, improve accessibility for older or disabled voters, accommodate citizens abroad and get the younger generation more involved in government. And you could still have in-person voting for those who lack access to the tech.

Hey, Estonia has offered Internet voting in elections since 2005. About 30 percent of voters take advantage of the option. No fraud, no hacks, no problems. So what's the holdup in the U.S.?

It's all about security, of course. Currently Internet voting is "a nonstarter," according to Aviel D. Rubin, technical director of Johns Hopkins University's Information Security Institute and author of the 2006 book *Brave New Ballot*. "You can't control the security of the platform," he told me. The app you're using, the operating system on your phone, the servers your data will cross en route to their destination—there are just too many openings for hacker interference.

"But wait," you're entitled to object, "banks, online stores and stock markets operate electronically. Why should something as simple as recording votes be so much more difficult?"

Voting is much trickier for a couple of reasons. Whereas monetary transactions are based on a firm understanding of your identity, a vote is supposed to be anonymous. In case of bank trouble, investigators can trace a credit-card purchase back to you, but how can they track an anonymous vote?

And credit-card and bank fraud goes on constantly. It's just a cost of doing business. But the outcome of an election is too important; we can't simply ignore a bunch of lost or altered votes.

So how does Estonia do it?

It's a clever system. You can vote online using a government ID card with a chip and associated PIN code—and a card reader for your PC. You can confirm the correct logging of your vote with an app. Parts of the software are available for public inspection.

You can change your vote as many times as you like online—you can even vote again in person—but only the last vote counts, diminishing the possibility that somebody forced your selection.

Unfortunately, three factors weaken this system's importance as a model for the U.S. First, Estonia is a country of about one million eligible voters—not around 220 million. Second, we don't have a national ID card.

Third, security experts insist that just because hackers haven't interfered with Estonia's voting doesn't mean they *can't*. In 2014 a team led by University of Michigan researchers found at least two points where hackers could easily change votes: by installing a virus on individual PCs or by modifying the vote-collecting servers. (The Estonian government disagrees with the findings.)

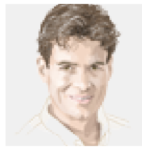
Meanwhile other countries' online-voting efforts haven't been as successful. Norway tested online voting systems in 2011 and 2013. But after controversy and the discovery that there was no improvement in voter turnout, the program was abandoned; it's back to paper for Norway.

At the moment, a few Americans *can* vote online: absentee voters from Alaska and many such voters in the military, for example. But they're informed that their votes may not be anonymous or secure.

Online voting isn't dead forever: great minds are working with biometric ID systems, two-factor authentication and new cryptographic systems in hopes of solving the problem. But the odds are overwhelming that you won't be casting your vote online in this year's election—or in the next few after that. In the meantime, we can still get our "I voted" stickers. SA

SCIENTIFIC AMERICAN ONLINE
MORE ABOUT THE FUTURE OF VOTING:
SCIENTIFICAMERICAN.COM/FEB2016/POGUE

Illustration by Jason Arias



Adam Tanner is a fellow at Harvard University's Institute for Quantitative Social Science. His next book, *The Big Health Data Bazaar: Uncovering a Multi-Billion-Dollar Trade in Our Medical Secrets,* will be published in January 2017.

For Sale: Your Medical Records

Data brokers legally buy, sell and trade health information, but the practice risks undermining public confidence

By Adam Tanner

For decades researchers have run longitudinal studies to gain new insights into health and illness. By regularly recording information about the same individuals' medical history and care over many years, they have, for example, shown that lead from peeling paint damages children's brains and bodies and have demonstrated that high blood pressure and cholesterol levels contribute to heart disease and stroke. To this day, some of the original (and now at least 95-year-old) participants in the famous Framingham Heart Study, which began in 1948, still provide health information to study investigators.

Health researchers are not the only ones, however, who collect and analyze medical data over long periods. A growing number of companies specialize in gathering longitudinal information from hundreds of millions of hospitals' and doctors' records, as well as from prescription and insurance claims and laboratory tests. Pooling all these data turns them into a valuable commodity. Other businesses are willing to pay for the insights that they can glean from such collections to guide their investments in the pharmaceutical industry, for example, or more precisely tailor an advertising campaign promoting a new drug.

By law, the identities of everyone found in these commercial databases are supposed to be kept secret. Indeed, the organizations that sell medical information to data-mining companies strip their records of Social Security numbers, names and detailed addresses to protect people's privacy. But the data brokers also add unique numbers to the records they collect that allow them to match disparate pieces of information to the same individual—even if they do not know that person's name. This matching of information makes the overall collection more valuable, but as data-mining technology becomes ubiquitous, it also makes it easier to learn a previously anonymous individual's identity.

At present, the system is so opaque that many doctors, nurses and patients are unaware that the information they record or divulge in an electronic health record or the results from lab tests they request or consent to may be anonymized and sold. But they will not remain in the dark about these practices forever. In researching the medical-data-trading business for an upcoming book, I have found growing unease about the ever expanding sale of our medical information not just among privacy advocates but among health industry insiders as well.

The entire health care system depends on patients trusting that their information will be kept confidential. When they learn that others have insights into what happens between them and their medical providers, they may be less forthcoming in describing their conditions or in seeking help. More and more health care experts believe that it is time to adopt measures that give patients more control over their data.

MULTIBILLION-DOLLAR BUSINESS

THE DOMINANT PLAYER in the medical-data-trading industry is IMS Health, which recorded $2.6 billion in revenue in 2014. Founded in 1954, the company was taken private in 2010 and relaunched as public in 2014. Since then, it has proved an investor favorite, with shares rising more than 50 percent above its initial price in little more than a year. At press time, IMS was a $9-billion company. Competitors include Symphony Health Solutions and smaller rivals in various countries.

Decades ago, before computers came into widespread use, IMS field agents photographed thousands of prescription records at pharmacies for hundreds of clerks to transcribe—a slow and costly process. Nowadays IMS automatically receives petabytes (10^{15} bytes or more) of data from the computerized records held by pharmacies, insurance companies and other medical organizations—including federal and many state health departments. Three quarters of all retail pharmacies in the U.S. send some portion of their electronic records to IMS. All told, the company says it has assembled half a billion dossiers on individual patients from the U.S. to Australia.

IMS and other data brokers are not restricted by medical privacy rules in the U.S., because their records are designed to

Illustration by Marina Muun

be anonymous—containing only year of birth, gender, partial zip code and doctor's name. The Health Insurance Portability and Accountability Act (HIPAA) of 1996, for instance, governs only the transfer of medical information that is tied directly to an individual's identity.

Even anonymized, the data command premium prices. Every year, for example, Pfizer spends $12 million to buy health data from a variety of sources, including IMS, according to Marc Berger, who oversees the analysis of anonymized patient data at Pfizer. But companies engaged in the data trade tend to keep the practice below the general public's radar.

Case in point: In the 1990s IMS started selling data on what individual U.S. physicians prescribe to patients to help drug companies tailor sales pitches to specific care providers. (HIPAA protects the identity of patients, not health care workers.) For years doctors did not realize that outsiders had insights on their prescribing habits. "At the time, it was taboo. It was forbidden to ever mention that topic," says Shahram Ahari, who used such data as a pharmaceutical representative visiting doctors for Eli Lilly from 1999 to 2000 and is now completing a residency at the University of Rochester. "It was the big secret." Asked for a response, an Eli Lilly spokesperson replied in an e-mail, "We have always been up front that we receive data from IMS."

Eventually physicians caught on and complained. Some considered such data gathering a privacy invasion; others objected to commercial firms profiting from details about their practices. A few states passed laws banning the collection of physician-prescribing habits. IMS challenged those rules all the way to the U.S. Supreme Court and—despite the arguments of 36 states, the Department of Justice, and numerous medical and consumer-advocacy groups supporting data limits—won its case in 2011 on corporate "free speech" grounds. The practice continues to this day, much of the time beyond public notice.

WHAT COULD GO WRONG?

ONCE UPON A TIME, simply removing a person's name, address and Social Security number from a medical record may well have protected anonymity. Not so today. Straightforward data-mining tools can rummage through multiple databases containing anonymized and nonanonymized data to reidentify the individuals from their ostensibly private medical records.

Indeed, computer scientists have repeatedly shown how easy it can be to crack seemingly anonymous data sets. For example, Harvard University professor Latanya Sweeney used such methods when she was a graduate student at the Massachusetts Institute of Technology in 1997 to identify then Massachusetts governor William Weld in publicly available hospital records. All she had to do was compare the supposedly anonymous hospital data about state employees to voter registration rolls for the city of Cambridge, where she knew the governor lived. Soon she was able to zero in on certain records based on age and gender that could have only belonged to Weld and that detailed a recent visit he made to a hospital, including his diagnosis and the prescriptions he took home with him.

"It is getting easier and easier to identify people from anonymized data," says Chesley Richards, director of the Office of Public Health Scientific Services at the Centers for Disease Control and Prevention. "You may not be identifiable from a particular data set that an entity has collected, but if you are a broker that is assembling a number of sets and looking for ways to link those data, that's where, potentially, the risk becomes greater for identification."

IMS officials say they have no interest in identifying patients and take careful steps to preserve anonymity. Moreover, there are no publicly recorded instances of someone taking anonymized patient data from IMS or a rival company and reidentifying individuals. Yet IMS does not want to talk too much about the gathering and selling of longitudinal data. At IMS, the CEO, the head of its Institute for Healthcare Informatics, the vice president of industry relations and the chief privacy officer declined to be interviewed for this article, but a company spokesperson did assist with fact-checking.

WHERE TO DRAW THE LINE?

APART FROM MAKING MONEY selling information to other businesses, IMS also shares some data with academic and other researchers for free or at a discount. The company has published a long list of medical articles that relied on its longitudinal data. For example, researchers learned that newer cardiovascular drugs reduce the length of hospital stays but do not prolong lives. In contrast, newer chemotherapy drugs are probably responsible for some of the recent decline in death rates from cancer in France.

Such benefits demonstrate that amassing medical data from multiple sources can have societal benefits. There is, however, a difference, says Jerry Avorn, a professor of medicine at Harvard Medical School, between "conscious, responsible researchers who only want to learn about medications' good and bad effects in a university medical school setting versus somebody sitting in the backroom [of a superstore] trying to figure out how can they sell more of product X by invading someone's privacy."

One small step toward reestablishing trust in the confidentiality of medical information is to give individuals the chance to forbid collection of their information for commercial use—an option the Framingham study now offers its participants, as does the state of Rhode Island in its sharing of anonymized insurance claims. "I personally believe that at the end of the day, individuals own their data," says Pfizer's Berger. "If somebody is using [their] data, they should know." And if the collection is "only for commercial purposes, I think patients should have the ability to opt out."

Seeking more detailed consent cannot, by itself, stem the erosion of patient privacy, but it will raise awareness—without which no further action is possible. Trust in the medical system is too vital to be sacrificed to uncontrolled market forces. SA

This reporting project was funded by a Reporting Award at New York University's Arthur L. Carter Journalism Institute.

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COMMENT ON THIS ARTICLE AT
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PREVIOUS AWARD WINNERS

'15

Dr. Bert Vogelstein, M.D.

For his breakthroughs in oncology research, which have spanned more than two decades and have formed the basis of modern cancer research.

'14

Jennifer Doudna, Ph.D. & Emmanuelle Charpentier, Ph.D.

For their co-discovery of the basis for adaptive immunity in bacteria, and the development of this system for facile genome editing.

'13

David Julius, Ph.D.

For his work elucidating the molecular mechanism for heat and pain perception.

'12

Victor R. Ambros, Ph.D. & Gary Ruvkun, Ph.D.

For their co-discovery of microRNAs as central regulators of gene expression and development.

'11

Napoleone Ferrara, M.D.

For his research on angiogenesis, the process of new blood vessel formation that plays a key role in cancer proliferation and a number of other diseases.

'10

Erik De Clercq, M.D., Ph.D. & Anthony S. Fauci, M.D.

For their pioneering work in understanding and combating viral diseases, particularly HIV/AIDS.

'09

Axel Ullrich, Ph.D.

For his pioneering work in applying molecular biology and molecular cloning to the discovery of protein therapeutics for the treatment of a wide range of diseases, including diabetes and cancer.

'08

Professor Marc Feldmann, FMedSci, FAA, FRS & Emeritus Professor Sir Ravinder Maini, FMedSci, FRCP, FRS

For their role in the discovery of tumor necrosis factor-alpha as an effective therapeutic target for rheumatoid arthritis and other chronic inflammatory conditions.

'06

Craig C. Mello, Ph.D., Nobel Laureate

For his role in the discovery of RNA interference and the elucidation of its biological functions.

SEVERAL STRANGE BODIES in the Kuiper belt beyond Neptune suggest the possible presence of an unseen large planet, which could even have a moon of its own.

THE SEARCH

SPACE

FOR PLANET X

In the far reaches of the solar system, a hidden planet larger than Earth may be lurking

By Michael D. Lemonick

Illustration by Ron Miller

Michael D. Lemonick is author of *Mirror Earth: The Search for Our Planet's Twin* (Walker Books, 2012). For 21 years he was a science writer for *Time* magazine. He is now *Scientific American*'s opinion editor.

SOMETHING VERY ODD SEEMS TO BE GOING ON OUT BEYOND PLUTO. ASTRONOMERS have known for more than two decades that the tiny former planet is not alone at the edge of the solar system: it is part of a vast cloud of icy objects known collectively as the Kuiper belt. But unlike most of their fellow travelers, and unlike the planets and most asteroids, which orbit between Mars and Jupiter, a small handful of Kuiper belt objects, or KBOs, have orbits that are decidedly weird. For one thing, they take unusually elongated paths around the sun, unlike the roughly circular orbits of most planetary bodies.

These badly behaving objects, which number between four and a dozen, depending on who is counting, share another orbital peculiarity as well. Like most KBOs, they orbit at an angle to the pancake-shaped plane where the planets live, rising above the pancake for part of the time, then plunging through to dip below for the rest. But unlike their frozen brethren, these objects all pass through the planetary plane at the same time that they make their closest swing toward the sun.

Or, to use a term even many astronomers find arcane, they have remarkably similar arguments of perihelion (AOP). "Normally," says Scott Sheppard, a planetary scientist at the Carnegie Institution for Science, "you would expect the arguments of perihelion to have been randomized over the life of the solar system." Maybe it is just a coincidence that these few bodies ended up with the same AOP: such a thing should happen, purely by chance, less than a few percent of the time. Those odds are something like getting 10 heads in a row when you flip a coin: pretty unusual but nowhere near impossible.

But those 10 heads could also mean your coin is loaded, and the same goes for these KBOs. Something may have forced the objects into this strange configuration—and that something could be a huge, unknown planet, significantly more massive than Earth, lurking out at the edge of the solar system: a super Earth (super Earths are planets up to roughly 10 times more massive than Earth). If such a hidden object—sometimes whimsically called "Planet X"—exists, it would orbit at least 10 times farther from the sun than Neptune—too distant and too faint to have been spotted by any telescope to date. Yet its sizable mass would have gravitational effects on the rest of the solar system—effects that might explain the odd orbits astronomers have seen.

"We don't have definitive proof yet that there's a planetary-mass body out there," says Nathan Kaib, a planet-formation theorist who is also at the Carnegie Institution. "But something funny is going on that we don't understand." And a growing number of astronomers are putting stock in the once ridiculed notion of the presence of a super Earth in our midst, Planet X.

As Kaib suggests, the evidence for a hidden planet is far from ironclad. Many astronomers still doubt the idea, and even those who invoke it as a possibility say they are not yet fully convinced. The history of astronomy is full of invisible mystery

IN BRIEF

A number of distant, icy objects circling the sun with weird orbits have led some scientists to suspect there may be more planets than we know of in the solar system.

The evidence, they say, supports the idea that one or more "super Earths"—planets up to 10 times more massive than Earth—may orbit far beyond Neptune.

These bodies would be too far and dim to have shown up in any existing telescope, but future observatories may be able to spot them, if they are out there.

planets, their existence inferred from the peculiar orbits of other objects. Some have turned out to be major discoveries. Others were false alarms. It may be that we do not know our solar system nearly as well as we thought we did. If there is a Planet X out there, it will necessitate a wholesale rewriting of some key chapters of the solar system's history.

ON THE TRAIL OF HIDDEN WORLDS

THE FIRST SEARCH for a hidden planet circling the sun came in the early 1800s, when scientists became increasingly convinced that Uranus, discovered accidentally in 1781 by the musician-turned-astronomer William Herschel, was not orbiting quite as Newton's law of gravity said it should. Several scientists posited that the gravity of a large, undiscovered planet was to blame—and in 1846 German astronomer Johan Galle spotted the gas giant Neptune, basically where his French colleague Urbain Le Verrier had calculated it should be. (There is good evidence that Galileo had actually seen Neptune as early as 1612 with his small, crude telescope but had assumed it was a star.)

In the early 1900s Boston aristocrat Percival Lowell began a search for another hidden planet based at his own personal observatory in Flagstaff, Ariz. This time the evidence came in the form of anomalies in the orbits of both Uranus and Neptune, pointing to the existence of yet another unseen giant planet. Early in 1930 a young assistant at Lowell Observatory named Clyde Tombaugh found a planet more or less where the calculations said it should be—a replay of the discovery of Neptune. "The Sphere, Possibly Larger than Jupiter and 4,000,000,000 Miles Away, Meets Predictions," the *New York Times* announced on March 14, 1930.

It did not, though. Within a few decades it became clear that Pluto is far from Jupiter's size and is actually smaller than Earth's moon. Its meager gravity could not possibly explain anomalies in the orbits of Neptune and Uranus—which turned out to be just as well because those anomalies faded away on further inspection. In that sense, Pluto was a false alarm.

In the big picture, however, its discovery was extraordinarily important. By the 1980s planetary scientists had begun to suspect that Pluto was not a puny planet orbiting all alone in the solar system's frozen outskirts but simply the brightest member of a vast, richly populated region known as the Kuiper belt. In 1992 the first KBO (besides Pluto, that is) was spotted with a telescope in Hawaii, and since then, observers have tallied another 1,500 or so. The 2005 discovery of Eris, which rivals Pluto in size and significantly outweighs it, threatened to open a floodgate that could have added several more planets to the existing roster of nine. That specter prompted the International Astronomical Union to demote Pluto from planet to dwarf planet in 2006.

RESHUFFLING THE SOLAR SYSTEM

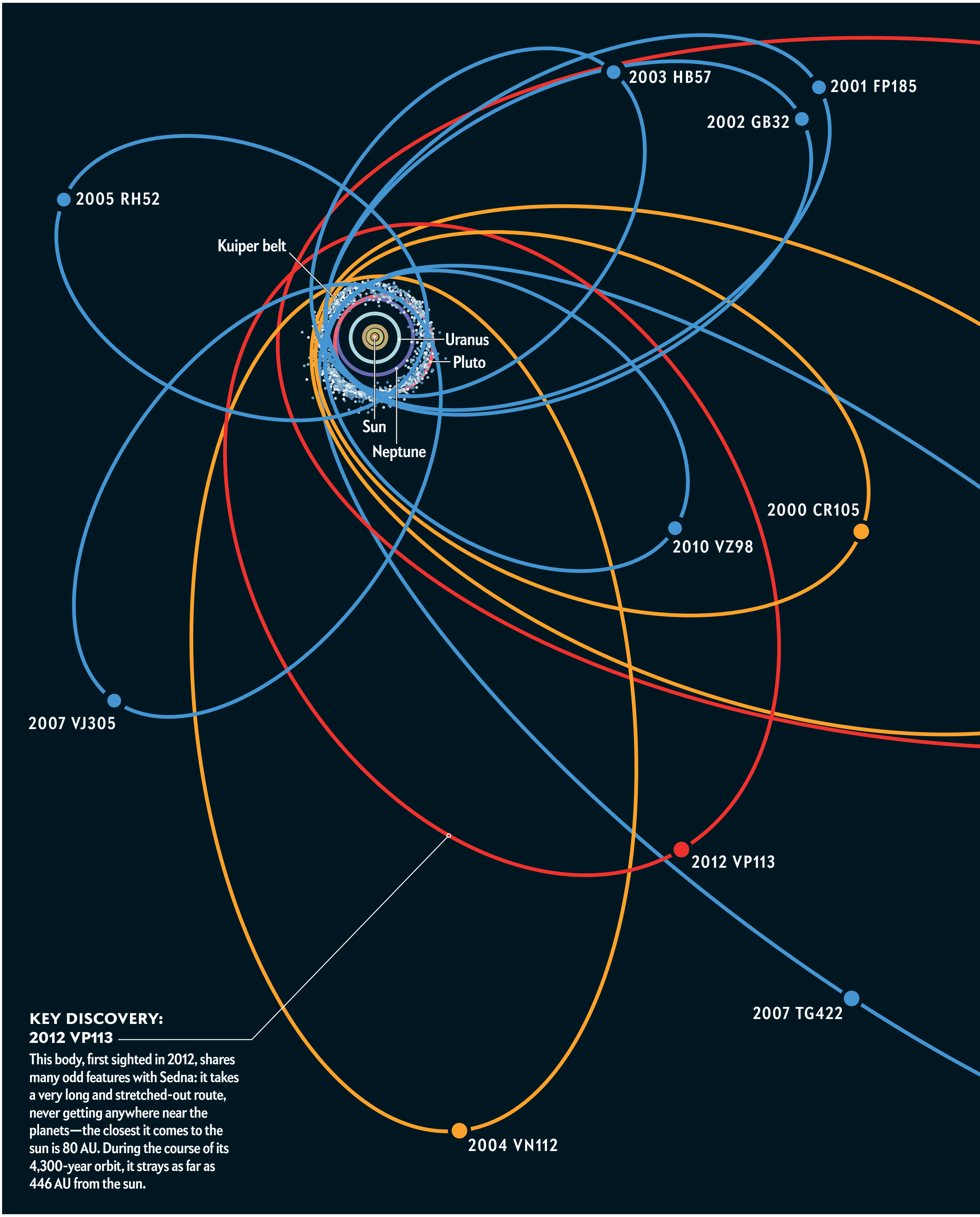
THE DISCOVERY of the Kuiper belt, in turn, lends credence to the latest search for a Planet X because it helps explain how such an object might have ended up so far from the sun that we still have not seen it. Computer simulations suggest that the icy bodies of the Kuiper belt should have formed somewhere in the neighborhood Neptune now occupies. Something must have flung them much farther out (or scattered them, to use the technical term) to their present positions. This observation led astronomers to theorize that a disruption took place during a chaotic period soon after the nascent planets congealed from the "protoplanetary disk" of gas and dust that swirled around the newborn sun. During this unsettled time, Jupiter, Saturn, Uranus and Neptune most likely shifted by hundreds of millions of kilometers from their initial orbits, their gravity sending the KBOs flying outward. Some simulations even point to the existence of a possible fifth gas giant that was ejected from the solar system entirely as the others adjusted their positions.

It is easily plausible that if a super Earth existed, it, too, could have been flung outward during this period of general mayhem. And because super Earths have proved to be common among the roughly 2,000 exoplanets discovered around other stars over the past couple of decades, it is also reasonable to suppose that there could once have been one circling our own sun. With that in mind, says Ben Bromley of the University of Utah, who collaborated with Scott Kenyon of the Harvard-Smithsonian Center for Astrophysics, "we ran some of mock-ups of what would happen to a super Earth scattered from the region where Jupiter and Saturn are today." In most cases, they found that the super Earth would be flung into a highly elliptical orbit, which would gradually become more and more stretched out until the planet was ejected from the solar system entirely. But if the scattering happened early enough—within about 10 million years after the formation of the planets, before the protoplanetary gas dissipated, Bromley says, "the super Earth could interact with the gas [gravitationally] and settle out in the boondocks in a more or less circular orbit."

The history of astronomy is full of invisible mystery planets, their existence inferred from the peculiar orbits of other objects.

That scenario is one way to make the kind of massive Planet X that Lowell set out to find in the early 1900s and the kind Galle and Le Verrier did find when they collaborated to discover Neptune half a century earlier. Another way to do it, Kenyon and Bromley found, was for the super Earth to form in place at perhaps 200 astronomical units (AU) from the sun, which is to say, 200 times the sun-Earth distance of 93 million miles. (Neptune, in contrast, orbits at about 30 AU from the sun.) Such in situ formation would be possible only if there were sufficient planet-forming material—pebble-size bits of rock and ice—orbiting out that far.

There is no direct evidence that this was ever the case in our own solar system, but there is quite good evidence that it happens with stars that are very much like the sun. "If you look at nearby solar-type stars," however, Kenyon says, "some of them have these debris disks with material extending to 200-ish AU away from the star itself. So it wouldn't be unprecedented." And although there is no proof that super Earths have formed at such a distance around


2003 HB57
2001 FP185
2002 GB32
2005 RH52
Kuiper belt
Uranus
Pluto
Sun
Neptune
2000 CR105
2010 VZ98
2007 VJ305
2012 VP113
2007 TG422
2004 VN112
KEY DISCOVERY:
2012 VP113
This body, first sighted in 2012, shares many odd features with Sedna: it takes a very long and stretched-out route, never getting anywhere near the planets—the closest it comes to the sun is 80 AU. During the course of its 4,300-year orbit, it strays as far as 446 AU from the sun.

Extreme Outer Objects

Far beyond the eight planets, the asteroid belt and even the distant Kuiper belt past Neptune, astronomers have seen roughly a dozen objects moving in strange orbits. These icy bodies all take elongated paths around the sun, and they share an odd feature—they seem to make their closest approach to the sun around the time that they cross the plane of the planets. One reason scientists suspect the presence of a large hidden planet, a so-called super Earth, in the far reaches of the solar system is that the gravitational pull of such a planet could account for these bodies' synchronized behavior.

10 OTHER NOTABLE EXTREMES

Astronomers have observed at least 10 other bodies that share some features with Sedna and 2012 VP113, such as an oblong orbit and a path that crosses the plane of the planets as it makes its closest approach to the sun. They all have average distances from the sun of at least 150 AU and can be divided into three categories based on their perihelion, or closest approach to the sun: those that never come nearer than 50 AU (the "inner Oort cloud"), those that approach between 40 and 50 AU from the sun (the "extreme detached disk"), and the "extreme scattered disk" of objects that swing in between 30 and 40 AU.

Known Extreme Outer Solar System Objects

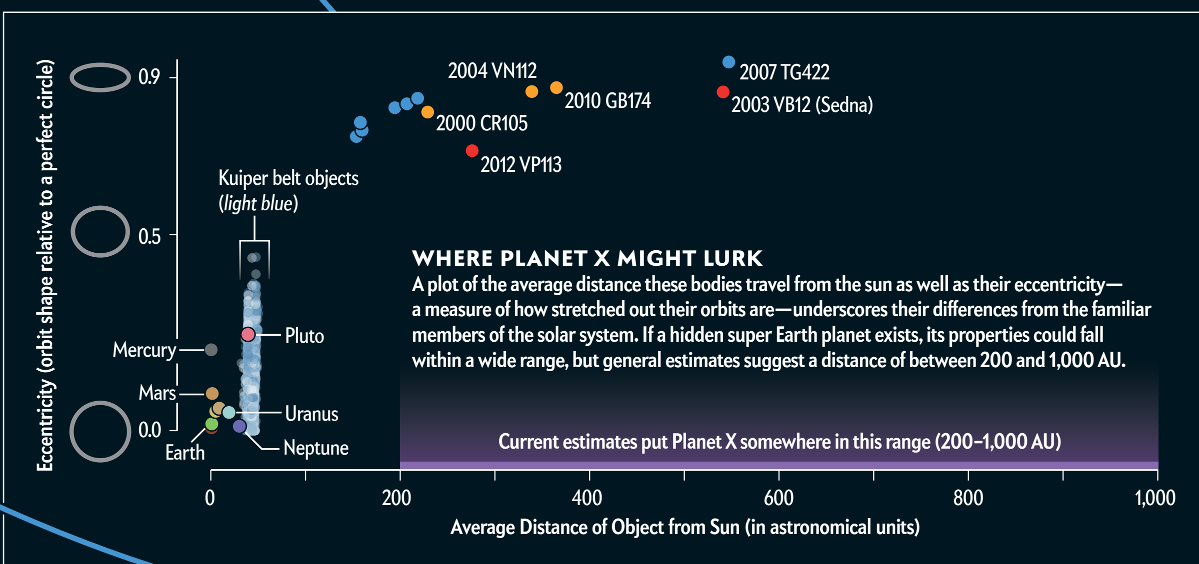
- Inner Oort cloud
- Extreme detached disk
- Extreme scattered disk

2003 VB12 (Sedna)

2010 GB174

KEY DISCOVERY: SEDNA

Discovered in 2003, Sedna is one of the most distant known objects in the solar system and has perhaps the oddest orbit ever seen. This icy rock, about 2,250 kilometers across, swings as far as 930 AU (the distance from Earth to the sun) from the center of the solar system and never comes closer than 76 AU in its 11,400-year oblong orbit.



WHERE PLANET X MIGHT LURK

A plot of the average distance these bodies travel from the sun as well as their eccentricity—a measure of how stretched out their orbits are—underscores their differences from the familiar members of the solar system. If a hidden super Earth planet exists, its properties could fall within a wide range, but general estimates suggest a distance of between 200 and 1,000 AU.

SOURCES: INTERNATIONAL ASTRONOMICAL UNION MINOR PLANET CENTER'S LIST OF TRANSNEPTUNIAN OBJECTS (*Kuiper belt object data*); SCOTT S. SHEPPARD *Carnegie Institution for Science* (*extreme outer solar system object data*)

Graphic by Jan Willem Tulp

these nearby stars, he says, "at least you have the basic ingredients." All these simulations were purely speculative when Kenyon and Bromley began working on them a decade or so ago. Nobody had seen even a hint that a super Earth was actually out there.

ENTER SEDNA

THAT SITUATION began to change with Sedna. In 2003 Mike Brown of the California Institute of Technology, along with two colleagues, spotted what was perhaps the strangest solar system object ever discovered up until that point. It was an icy body, about 2,250 kilometers across, and similar in many ways to Pluto, Eris and other KBOs. Its orbit, however, had not been seen before. Sedna never comes closer than 76 AU from the sun, or more than twice as far away as Neptune, on its highly elongated 11,400-year orbit, and it retreats to more than 930 AU—31 times as far as Neptune—at its most distant.

"Nobody had thought an object like this could exist," Chad Trujillo says, "and nobody had an explanation of how it got there."

"Sedna was really surprising," says co-discoverer Chad Trujillo, now at the Gemini Observatory in Hawaii, "because it was completely unexplained." Its stretched-out orbit resembled those of long-period comets, but unlike Sedna, these have one orbital end firmly anchored by the gravity of the giant planets. Sedna appeared unanchored to anything. "Nobody had thought an object like this could exist," Trujillo says, "and nobody had an explanation of how it got there."

Over the next decade or so observers found 10 other, smaller objects whose orbits are also elongated and that never come within shouting distance of Neptune. By itself, this was not especially noteworthy: none of them was nearly as extreme as Sedna either in the shape of its orbit or in how far beyond Neptune its perihelion came—that is, its closest approach to the sun. But all of them, along with Sedna itself, shared a similar argument of perihelion, the unusual orbital parameter that describes how far above or below the plane of the solar system an object is when it reaches perihelion. And that seemed … odd.

Things got significantly odder in 2014, when Trujillo and Sheppard announced in *Nature* that they had discovered a second Sedna-like object, about half as big as Sedna itself, after searching for something like it for a decade. "If you're a biologist," Trujillo says, "and you find some weird creature, you're pretty sure there's got to be more like it out there." Likewise in astronomy, he says—unless that first creature was a total fluke. "Maybe this one object happened to be thrown in this orbit for reasons we don't understand," he says, "but you don't really know until you find another one." Now they had.

Known provisionally as 2012 VP_{113}, its eccentric, 4,300-year orbit has a perihelion of 80 AU and an aphelion—its farthest retreat from the sun—of 446 AU. Like Sedna, 2012 VP_{113} is fully detached from Neptune gravitationally. And crucially, its argument of perihelion is very similar to Sedna's, as well as to that of a handful of other, less Sedna-like KBOs. It was that last factor that led to a provocative line buried well down in the *Nature* paper. "This suggests," wrote Trujillo and Sheppard, "that a massive outer Solar system perturber may exist." The perturber, they hypothesized, could be a super Earth orbiting up to 250 AU from the sun, whose gravity might have influenced the smaller objects and synchronized their arguments of perihelion. "I don't think anyone was really thinking seriously about a massive, undetected planet before this," says Meg Schwamb of Yale University. "But the Trujillo and Sheppard paper really brought it into play."

Then, in September 2014, a paper in *Monthly Notices of the Royal Astronomical Society Letters* by two relatively obscure Spanish astronomers, brothers Raúl and Carlos de la Fuente Marcos of the Complutense University of Madrid, upped the ante. Based on the orbits of Sedna, 2012 VP_{113} and smaller bodies, they argued that there might not be just one super Earth. Their analysis "strongly suggest[ed]" that at least two planets might exist beyond Pluto. "Our unpublished calculations," Raúl says, "suggest that the hypothetical planets should be at least two, but probably fewer than 15, Earth masses."

Like Sheppard and Trujillo, the de la Fuente Marcos brothers do not claim to be making a solid prediction. Both teams say only that the existence of a super Earth is plausible. If it exists, however, astronomers' confidence that they fully understand our own solar system will be upended.

DOUBTS REMAIN

ALTHOUGH A HIDDEN PLANET X is a tempting explanation for the oddities of Sedna and its ilk, it is not the only option. Another possibility, says planet-formation theorist Hal Levison of the Southwest Research Center is that Sedna, 2012 VP_{113} and the rest were thrown into their distinctive orbits while the sun was still part of its original birth cluster of thousands of stars that congealed from a single gas cloud. Before the cluster drifted apart, those stars would have been nearby enough to distort the orbits of objects in the outer solar system, sending them inward on long, stretched-out trajectories. Or, Sheppard says, the orbital elongations could have come from galactic tides—that is, a stronger pull from one direction than from another as the sun passes close to higher-density regions on its orbit around the center of the Milky Way. "We've run some simulations like that," Sheppard says, "and nothing has shown up. So it doesn't appear that that's likely, but there are a lot of other possibilities kind of like that out there."

Any of these effects could have put the objects on their oblong orbits, but only the super-Earth hypothesis could give them such closely matching arguments of perihelion. That or pure chance. The 12 objects Sheppard and Trujillo cite in their paper may sound like a lot, but given that there are millions of Kuiper belt objects, Sheppard says, "that's a statistically marginal number."

The case for Planet X from the odd orbits of Sedna and its fellows gets even more marginal if you agree with Schwamb and her collaborator Ramon Brasser of the Tokyo Institute of Tech-

SCIENTIFIC AMERICAN ONLINE Listen to a podcast about evidence for Planet X at ScientificAmerican.com/feb2016/planet-x

nology. “Work we’ve done recently,” Schwamb says, “shows there are really only four objects like Sedna.” The rest of the 12 do not come all that close to Neptune, she says, but they come close enough that they could be feeling its gravity. Neptune itself could therefore be the Planet X that explains their closely matching arguments of perihelion. And if 12 objects are considered statistically marginal, four is even more so—although “marginal” in science means something slightly different than it does in the everyday world. “The alignment of the four remaining objects,” Brasser says, “would happen by chance only 1 percent of the time.” Long odds, however, are not a slam dunk. “Just because you can say a planet is possible,” Schwamb says—which she agrees it is—“doesn’t rule it in.”

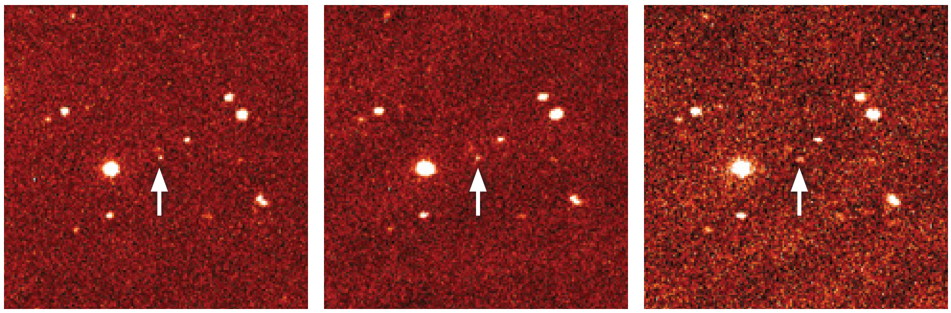
Planetary scientists have learned that lesson more than once. In the 1980s University of California, Berkeley, physicist Richard Muller thought he could explain many past mass extinctions of species on Earth by invoking a dim star or a brown dwarf—an object less massive than a star but more massive than a planet—orbiting the sun at a distance of roughly 10,000 AU, or about 1.5 light-years. Once every 26 million years, more or less, goes the theory, the object he called Nemesis kicks a knot of comets out of the Oort cloud, a still hypothetical shell of icy bodies that surrounds the solar system far beyond Sedna or anything else astronomers have ever seen. The Oort comets fall in toward the sun. Some of them slam into Earth, and there goes a large fraction of the species on our planet.

But just like today’s arguments for Planet X, the theory was only barely plausible, and searches for Nemesis have consistently turned up empty. More recently, John Matese and Daniel Whitmire, both at the University of Louisiana at Lafayette, postulated a Jupiter-size planet in the far outer solar system to explain what seemed to be an excess of long-period comets coming in from one direction in the sky. “It was,” Schwamb says, “a paper in the literature,” which is scientific shorthand for “I never bought it in the first place.” Sure enough, a sensitive survey by NASA’s Wide-field Infrared Survey Explorer (WISE) telescope saw nothing. “We would have been able to see an object as small as Jupiter out to about maybe 30,000 to 40,000 AU from the sun,” says Kevin Luhman of Pennsylvania State University, who conducted the search, “and we would have been able to see an object as small as Saturn out to maybe 10,000 or 15,000 AU from the sun.” They found nothing. A super-Earth-size Planet X would be much closer but also so much dimmer that it would not have shown up in this survey.

SO IS IT THERE OR NOT?

WITH NO MORE than 12 unusual objects to guide them, planetary scientists cannot say at this point whether our solar system is host to a super Earth or not. They can say only that the hypothesis is consistent with the observations. Identifying more objects with similar orbital characteristics is crucial, which is why astronomers are so excited about a new object announced last November. Known as V774104, it has a perihelion even farther from the sun than Sedna’s. It is too early to know whether its orbit confirms or rejects the possibility of an undiscovered giant planet, says Sheppard, who led the discovery team. It is also too early to say much about the 40 or so other distant objects Sheppard’s team found at the same time in what he calls “the deepest, widest survey of the outer solar system ever conducted.” But the more the researchers find, the better their chances of saying definitively whether something massive lurks out there.

To improve their chances even more, planetary scientists are eager to get their hands on the Large Synoptic Survey Telescope (LSST), scheduled to come online in northern Chile by 2018. It will not be any bigger than the largest telescopes currently in use, but its field of view will be much wider, allowing it to search much broader swaths of sky. At present, Trujillo says, astronomers have surveyed about 10 square degrees of sky—the full moon, for comparison, covers a quarter of a square degree—in search of faint, distant objects. The LSST, he says, “will be able to survey tens of thousands.”



THREE IMAGES taken roughly an hour and a half apart at the Palomar Observatory in California show the movement of a faint object astronomers dubbed Sedna. The odd orbits of Sedna and similar bodies suggest there might be a hidden planet far beyond Pluto.

COURTESY OF NASA, JPL AND CALTECH

If a super Earth is out there, and if it is large and bright enough, the LSST could find it. Or perhaps someone else already has. This past December, observers claimed they’d taken direct images of what could be a different super Earth using the Atacama Large Millimeter/submillimeter Array in Chile. Most of their colleagues were highly skeptical, but more observations could change that. Or perhaps some other telescope has inadvertently imaged our local super Earth. “Maybe it’s sitting around on somebody’s hard drive, and they just never noticed it because they weren’t looking for it, or they weren’t looking in the right way,” Trujillo says. “People tend to see what only they’re looking for.” SA

MORE TO EXPLORE

A Sedna-like Body with a Perihelion of 80 Astronomical Units. Chadwick A. Trujillo and Scott S. Sheppard in *Nature,* Vol. 507, pages 471–474; March 27, 2014.

Extreme Trans-Neptunian Objects and the Kozai Mechanism: Signalling the Presence of Trans-Plutonian Planets. C. de la Fuente Marcos and R. de la Fuente Marcos in *Monthly Notices of the Royal Astronomical Society Letters,* Vol. 443, No. 1; pages L59–L63; September 1, 2014.

FROM OUR ARCHIVES

Planet X. Henry Norris Russell; July 1930.

scientificamerican.com/magazine/sa

HEALTH

bitter taste bodyguards

Bitter taste receptors are not only on the tongue but throughout the body, where they defend us against microbial invaders

By Robert J. Lee and Noam A. Cohen

DOUBLE DUTY: Taste receptors, found in buds (*orange*) on the tongue, also play a disease-fighting role. This image shows a one-millimeter-wide section.

Robert J. Lee is an assistant professor in the department of otorhinolaryngology–head and neck surgery and in the department of physiology at the Perelman School of Medicine at the University of Pennsylvania. A molecular biologist, he has spent more than a decade studying cells that line inner surfaces in the nose and lung.

Noam A. Cohen is an associate professor in the department of otorhinolaryngology at the University of Pennsylvania. He is a surgeon with 15 years of clinical experience and director of rhinology research at the school.

IMAGINE THE WORST COLD YOU'VE EVER had in your life. Your nose feels completely blocked. You struggle for air. The pressure in your sinuses sends pain streaking around your head. You can't smell, so eating food is like chewing on cardboard, you are nauseated and you feel utterly miserable. Now imagine that the symptoms, even if they ease for a week or so, always come back. You are never free. Ever.

Unfortunately, this is the very real life of patients with chronic sinusitis—technically called chronic rhinosinusitis—a disease of the nose and other regions of the upper airway that affects about 35 million Americans. For many of these people, treatment often involves prolonged courses of antibiotics and steroids. If those drugs do not work, sufferers have to undergo delicate surgery to clean out infected cavities in their skull. This surgery seems to be happening more often these days because modern society's excessive use of antibiotics has perversely caused those medications to become less effective. Today one out of every five antibiotic prescriptions in the U.S. is for an adult with rhinosinusitis, and the illness has become part of a vicious cycle, contributing to the rise of such dangerous antibiotic-resistant bacteria as methicillin-resistant *Staphylococcus aureus* (MRSA).

That's where we come into this story. We want to break the cycle. Along with many other researchers, we are working to understand the immune defense mechanisms that cells on the inner surface of the airway, known as epithelial cells, deploy against respiratory infections. The average person breathes in more than 10,000 liters of air a day, much of it through the nose, and that air contains countless bacteria, fungi and viruses. Our nose is the front line of respiratory defense. Every time we breathe, particles of debris, viruses, bacteria and fungal spores get trapped there. Yet amazingly, most people walk around breathing freely without any kind of airway infection.

It turns out that one previously unsuspected reason may be, literally, on our tongue. Proteins there—called taste receptors—that detect bitter flavors have been found to do double duty, also defending us against bacteria. Our own research has shown that these receptors, also found in the nose, trigger three bacteria-fighting responses. First, they send signals that cause the cells to flick invaders away by moving cilia—tiny, hairlike projections—on the cells' surface. Second, the receptor proteins tell cells to release nitric oxide, which kills bacteria. Third, receptors signal still other cells to send out antimicrobial proteins called defensins.

Even more astonishing, several researchers have found these receptors not just on the tongue and nose but elsewhere in the airway, as well as in the heart, lungs, intestines and more body organs. Along with other scientists, we now believe these receptors are part of an innate human immune system that is different—but potentially faster—than the more familiar features of antibodies and invader-fighting cells that circulate through our body. It can take many hours or days for the immune system to produce specific antibodies against viruses or bacteria. The taste receptor responses, though more of a general reaction and less tightly targeted to particular bacteria, happen in just minutes—a true early-warning system.

A TASTE FOR DANGER

IF YOU THINK of taste receptors as sentinels that react to substances that come into the body, then their immune system role makes sense. When they reside on the cells that form taste buds on the tongue, the receptors prompt the cells to send signals to the brain that tell it about the nutritional value or potential toxicity of the foods we put in our mouth. The tongue detects five basic types of tastes: bitter, sweet, salty, sour and savory, also known as umami. Our sense of taste acts as the gatekeeper to the digestive system, giving us information about the food we are eating so that we can decide whether or not to swallow it. Bitter taste receptors can detect the presence of poisonous plant chemicals, including a class of chemicals called alkaloids that includes strychnine and nicotine. The tastes we today describe as "bitter" are often perceived by our brain as unpleasant because receptors evolved to signal the presence of potentially harmful chemicals.

Warning against harm is key to survival, which may be why there are so many different bitter receptors. Sweet, salty, sour and umami have only one type of receptor each, but at least 25 types of receptors detect bitter compounds. Known as taste family type 2 receptors, or T2Rs, they probably evolved to recog-

IN BRIEF

Proteins that detect bitter taste exist not just on the tongue but throughout the body, in organs that never come into contact with food.

Called taste receptors, these proteins trigger extreme rapid-response defenses that can kill bacteria, new research has found.

Stimulating these receptors with bitter compounds may heighten natural immune responses and reduce our reliance on antibiotics.

PRECEDING PAGES: SCIENCE SOURCE

nize and protect us from swallowing a wide variety of poisons.

Early hints of a role elsewhere in the body emerged in 2009, when researchers at the University of Iowa discovered T2Rs on epithelial cells that line the lungs. A sticky layer of mucus on top of these cells traps microbes and irritants when we inhale them. Then the tiny cilia on the cells beat eight to 15 times each second, in synchrony, to push the irritants toward the throat, where you swallow them or spit them out. The Iowa team discovered that cilia in human lung cells actually beat faster when their T2Rs were stimulated by bitter compounds, suggesting that the T2Rs help the airway clear potentially dangerous inhaled substances that, in the mouth, would taste bitter.

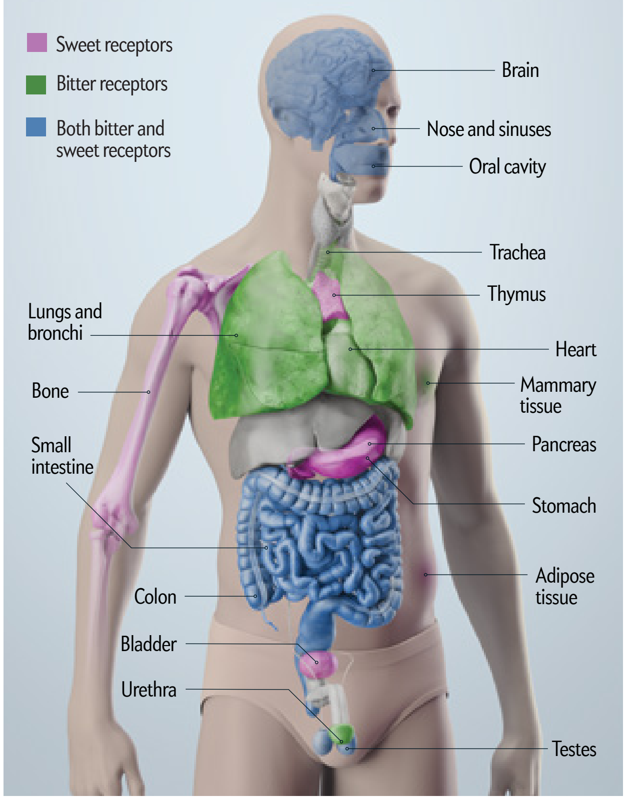
Around the same time, investigators at the University of Colorado Anschutz Medical Campus were studying bitter taste receptors found on a special type of cell in the rat nose that appears to react to irritants. They discovered that these cells, termed solitary chemosensory cells, become more active when they detect bacterial molecules called acyl-homoserine lactones (AHLs). AHLs are released by dangerous gram-negative bacteria when these microbes form biofilms. Biofilms are communities of bacteria, such as *Pseudomonas aeruginosa,* that stick to one another by forming a matrix, making them up to 1,000-fold more resistant to antibiotics than less organized bacteria are and thus much harder to kill. The researchers from Colorado showed the biofilm-inducing AHL molecules stimulated activity in the chemosensory cells. AHLs were thus the first specific bacterial chemical shown to stimulate cells with bitter taste receptors, supporting the notion that receptors respond to outside invaders.

Intrigued by these findings, we began searching for taste receptors in human nasal epithelial cells in 2011, collaborating with experts in taste at the Monell Chemical Senses Center in Philadelphia, a premier institution for smell and taste research. Our investigation started out as a small side project to determine whether we could find bitter taste receptors in nasal cells just as the Iowa researchers found them in the lung. But it quickly became a big focus in our laboratory when we saw hints that certain taste receptors might affect people's susceptibility to rhinosinusitis.

ANATOMY

Taste Receptors All Over the Body

Although they are named because of their role on our tongue, bitter and sweet taste receptors have recently been discovered in many organs and tissues that never come into contact with food. In at least some of these body parts, particularly the airway, these taste receptors play an important role in immunity.



SUPERTASTERS

IN OUR SEARCH, we looked specifically for one bitter taste receptor, T2R38, the most well studied of the T2R family. The human T2R38 protein comes in several varieties, the result of slight differences, called polymorphisms, in the genes that encode them. And we did find many of the most common versions in the cilia lining the nose and sinuses.

The discovery of this receptor menagerie led us to explore how the different T2R38 forms affect the behavior of sinus and nasal cells. Two forms in particular have dramatically different effects on taste when present in the tongue. One of these versions is very sensitive as a taste detector in the mouth, and the other one does not respond at all. About 30 percent of Caucasians inherit two copies of the gene for the insensitive T2R38 variant (one from each parent), and these individuals are "nontasters" for certain bitter compounds. About 20 percent of Caucasians have two copies of the gene for the functional T2R38, and these individuals perceive those same compounds as intensely bitter; such people are known as "supertasters." Those with one copy of each gene variant fall somewhere in between these extremes.

Examining tissue removed during sinus and nasal surgeries, we compared the behaviors of nasal cells possessing one or the other of these two forms. (We knew which types were in the cells by sequencing their genes.) To get the receptors to react, we exposed the cells to a chemical called phenylthiocarbamide (PTC), often used for T2R38 taste testing. And we were excited to see that the cells from supertaster patients, but not those from the nontasters, produced large amounts of nitric oxide.

This finding gave another boost to our idea of a taste-immunity connection. Nitric oxide does two important things against bacteria in the airway. It can stimulate airway cells to increase ciliary beating. It can also directly kill bacteria. Because nitric oxide molecules form a gas, they can rapidly diffuse out of the cells lining the airway into the mucus and then into bacteria. Once inside, the substance can damage membranes, enzymes and DNA. Ordinarily our sinuses produce large amounts of nitric oxide that travel through the airway, which helps to keep it free of infection.

These twin modes of antibacterial activity made us think that different T2R38 versions might alter people's susceptibility to upper respiratory infections. And indeed, in the lab, we found that

Illustration by Anatomy Blue

the nitric oxide produced by supertaster nasal cells during T2R38 activation caused faster ciliary beating and directly killed more bacteria than nontaster nasal cells. We next discovered that the same class of bacterial compounds that were previously shown to activate mouse nasal chemosensory cells, AHLs, directly activates human T2R38 receptors. Nasal cells from supertasters detect bacterial AHLs through T2R38 and produce nitric oxide, whereas cells from nontasters do not. These properties make cells from supertasters much better at killing AHL-producing bacteria than cells from nontasters. From these observations, we concluded that the T2R38 bitter receptor is used by airway epithelial cells to detect bacterial activity and activate defenses.

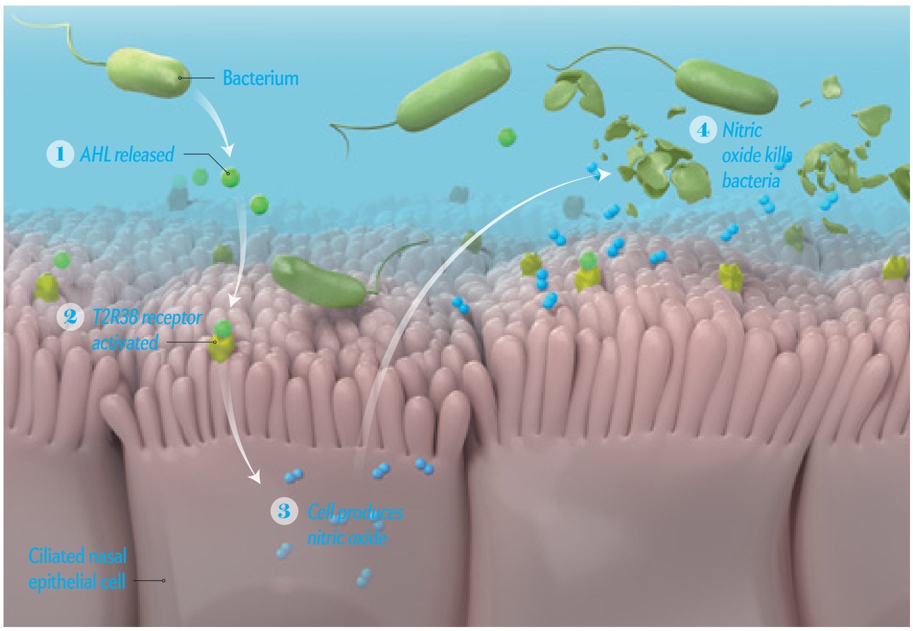
IMMUNE RESPONSE

Two Defense Systems That Use Bitter Receptors

Cells in the human airway play roles in defending the body against invading bacteria. Two of these cell types (*diagrams*) have been shown to use bitter taste receptors in different ways to detect and repel the invaders.

Hair-Trigger Reaction

Bacteria of the gram-negative class, when they infect the nose, release chemicals called acyl-homoserine lactones, or AHLs (1). This chemical is detected by bitter taste receptors from a group called T2R38s, which sit in hairlike projections called cilia that extend from cells on the inside surfaces of the nose (2). The cells, known as nasal epithelial cells, release a gas, nitric oxide, in response (3). The gas diffuses into the bacteria, killing them (4). Cilia on the cells also beat back and forth, flicking bacteria away.



Start and Stop

Other cells, called solitary chemosensory cells, have both bitter taste receptors (T2Rs) and sweet taste receptors (T1Rs). Infectious bacteria release a compound that contacts bitter receptors (1), and then the cells release calcium (2). The calcium signals nearby cells to release compounds called defensins (3). Defensins hurt and kill bacteria (4). Then sweet substances such as glucose (5) increase because they are no longer eaten by bacteria. Glucose is detected by sweet receptors (6), which reduce bitter receptor activity, probably preventing an overreaction.

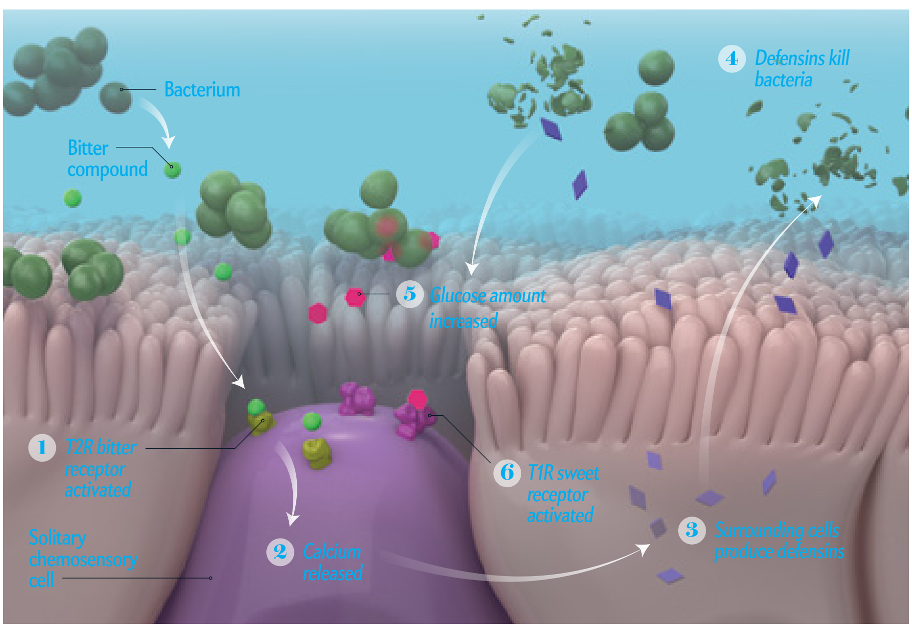


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Illustration by AXS Studio

Since our discovery of T2R38 in cilia of human nasal epithelial cells, our knowledge of the role of taste receptors in the nose has expanded even further. These receptors also appear in solitary chemosensory cells in the human nose, similar to those found in mice. Solitary chemosensory cells really are solitary, dispersed widely throughout the nasal cavity and making up about only 1 percent of the cells there. The cells have both T2R bitter receptors and T1R sweet receptors. When T2Rs in these cells get stimulated, we have found, the solitary cells release a signal to surrounding cells that prompts them to release antimicrobial proteins called defensins into the airway mucus. Defensins are capable of killing many illness-causing bacteria, including *P. aeruginosa* and MRSA.

The sweet taste receptors, when stimulated, shut down the activity of the bitter ones, probably to prevent cells from releasing too many proteins at an inappropriate time. Sweet receptors had already been found in other body parts, such as the pancreas, where they sense sugars in the blood and stimulate cells to produce insulin that regulates glucose levels. Our work on the nasal cells, however, showed that sweet and bitter receptors in the same cell have opposing roles.

These experiments suggest to us that taste receptors constitute an early-warning arm of the airway immune response. They seem different from the most well-studied class of early-warning proteins, which are known as toll-like receptors (TLRs). The TLRs also activate immune responses when stimulated by certain bacterial molecules, as the T2Rs appear to do. But there is at least one important difference: some TLR responses—such as signaling genes to start creating antibodies that mark invaders for destruction—are much slower, taking several hours or even days. T2R38 and its bitter cousins, in contrast, produce responses within seconds to minutes. These taste receptors might be most important during the onset of infection by activating a kind of "locked and loaded" instant reaction. Other immune receptors may be more crucial for fighting a prolonged infection, calling up the troops when the first response is not sufficient.

VULNERABLE PEOPLE

THE LARGE NUMBER of genetic varieties in T2R bitter taste receptors makes their role in immunity even more intriguing. Most of the 25 bitter receptors have genetic variations that increase or decrease their abilities, thus making people who have them more or less sensitive to bitter-tasting substances. If a reaction to bitterness is indeed part of the immune response to invading bacteria, these same genetic variations may also create differences in the way people combat infections. Increased bitter receptor function may confer greater protection against infection, whereas lower function may increase susceptibility.

We have begun to test this idea in people and have hints that it is correct. The millions of patients with chronic rhinosinusitis constitute a natural test population and a group in need of help. When given quality-of-life questionnaires, rhinosinusitis patients report worse scores than patients with several heart and lung diseases. Plus, rhinosinusitis patients can develop dangerous lung infections and exacerbate lower airway diseases such as asthma. We have looked at microbiology cultures from patients with the condition. Supertasters did get rhinosinusitis—they are not immune—but they had a much lower frequency of nasal infections with gram-negative bacteria than did nontasters. That makes sense because gram-negative bacteria produce AHLs, the compounds that, by triggering receptors, lead cells in these people to release microbe-killing nitric oxide. Other bacteria do not produce AHL, so they would not run afoul of these immune defenses.

Further clinical research has supported the role of T2R38 in sinusitis. Two studies from our group at Pennsylvania demonstrated that people with two copies of the T2R38 supertaster gene are less likely to get severe rhinosinusitis than are patients with two nontaster copies or even patients with one copy of each. A study by otolaryngologist Martin Desrosiers of CHUM in Montreal and his colleagues verified that the T2R38 nontaster gene occurs more often in patients than in healthy people. That study found that rhinosinusitis severity is also associated with variants in two other T2R receptor types, T2R14 and T2R49.

In organs beyond the nose, connections between taste receptors and immunity are starting to show up. In 2014 scientists showed that when confronted with pathogenic *Escherichia coli,* chemosensory cells in the urinary tract use T2Rs to stimulate the bladder to release urine. This could be the body trying to flush bacteria out and prevent bladder infections. Another recent study has shown that white blood cells—which include neutrophils and lymphocytes and are crucial components of the immune system—also use T2R38 to detect *Pseudomonas* AHLs.

Right now we want to learn whether chemicals that activate T2R receptors can work as medicine for rhinosinusitis patients by stimulating stronger bacteria-killing responses. The vast array of bitter compounds in foods we eat and drink every day could be potential therapeutics, including humulones and lupulons from hoppy beers, isothiocyanates from green vegetables such as Brussels sprouts and bitter chemicals from citrus such as limonin. Absinthin, a bitter chemical isolated from the wormwood plant and found in the liquor absinthe, has been shown to stimulate solitary chemosensory cell T2Rs. In our lab, we are investigating several formulations that could work as drugs. Novel medications based on bitter compounds might someday be used to combat infection without using conventional antibiotics.

We believe it is also possible that taste or genetic testing of T2Rs might eventually be used to predict susceptibility to infections. The natural variations in these taste receptors may help us answer an age-old question: Why do some people frequently get respiratory infections, whereas others never seem to get sick? Using bitter receptors to solve this puzzle would be sweet indeed. SA

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Collect Wis

SOCIAL BEHAVIOR

Ant colonies work without central control. Knowing how they do this might help us understand other systems that have no leader, from brains to the Internet

By Deborah M. Gordon

In the 2015 summer blockbuster *Ant-Man,* the character Hank Pym, a scientist who has invented a suit that can shrink a person down to the size of an insect, remarks that ants can perform amazing feats, but they need a leader to tell them what to do. Pym wears a small device behind his ear that allows him to instruct the ants to act as a phalanx of attackers that helps the ant-sized human hero defeat an evil mastermind.

The idea that ants have commanders that set the agenda and orchestrate their activities resonates because of the hierarchical way in which many human organizations work, and it provides a convenient premise for a Hollywood film whose heroes are people. There's just one problem: it's wrong. Ants never march in lockstep, united in obedience to a single command. In the real world, the often random and apparently inept actions of individual ants, each without any sense of a common goal, combine to allow colonies to find and collect food, build nests, form trails and bridges, defend their host plants from herbivores or cultivate gardens—all without supervision. Ants

ive dom of Ants

do not need a leader, and no ant ever tells another what to do.

Ant colonies are not the only systems in nature to operate without central control. Collective behavior, without instruction from on high, occurs everywhere, from the flock of starlings that wheels in the sky to the network of neurons that allows you to read this sentence to the molecules that work with genes to make proteins. All the many outcomes of collective behavior are accomplished through simple interactions among the individual actors, whether they are ants, birds, neurons or molecules.

When as a graduate student I began to study systems without central control, I looked for a system in which the interactions were easy to observe—and ants were not hard to find. There are more than 14,000 species distributed across every terrestrial habitat on Earth. They build nests in the ground, in hollow twigs and acorns, under rocks and in leaves high up in the forest canopy. They vary enormously in what they eat, from nectar to fungi to other insects. All ant species exhibit collective behavior, so they provide an excellent opportunity to learn how such behavior has evolved to solve the diverse ecological problems that ant colonies encounter.

My studies of several kinds of ants in a variety of ecological settings, from desert to tropical forest, show that they each use interactions differently—for example, to ramp up activity, slow it down or just keep it going. These findings suggest a fit between the ecological situation and the way that simple interactions adjust collective behavior. Evolution may have converged in a range of systems without central control to produce similar algorithms to meet similar environmental challenges.

Deborah M. Gordon is a biologist at Stanford University. Her research focuses on collective behavior in ants.

SIMPLE INTERACTIONS

ALL ANT SPECIES have certain characteristics in common, including similarities in how the ants carry out tasks. Ants live in colonies composed of many sterile female workers (the ants you see walking around) and one or more fertile females that remain inside the nest. Although these fertile females are called queens, they do not wield any political power—all they do is lay the eggs. Neither the queen nor any other ant can assess what needs to be done and give orders to others. In addition, all ants possess a keen sense of smell capable of distinguishing among hundreds of chemicals. Ants smell with their antennae. When one ant touches another with its antennae, it assesses the odor carried in the other ant's greasy outer coating of so-called cuticular hydrocarbons, which help to prevent desiccation. Scientists know that in some species the chemistry of the cuticular hydrocarbons responds to environmental conditions. A harvester ant that forages out in the hot desert sun comes to smell differently from an ant that spends most of its time in the nest. As a result, an ant's odor reflects its task.

To learn how ants use antennal contacts, Michael Greene of the University of Colorado Denver and I conducted experiments in which we coated small glass beads with extracts of the cuticular hydrocarbons from ants that carry out particular tasks, and then we introduced the beads inside ant nests. We found that when one ant touches another with its antennae, the message it receives is simply that it has met an ant of that particular odor. It turns out the rate of interactions is key to how the insect responds. In our experiments we were able to elicit changes in a colony's behavior by changing the frequency of the ants' encounters with the glass beads.

How do ant colonies organize their work using only simple olfactory interactions? For the past 30 years I have been studying harvester ants in the southwestern U.S. It seems that for harvester ants, the need to conserve water has been a driving force in the evolution of the process that uses interactions to regulate foraging activity. Harvester ants subsist on the seeds of grasses and annual plants, which provide both food and water to the colony. But a colony must spend water to get water. Foragers lose water just by being outside searching for seeds. An outgoing forager does not leave the nest until it has had enough encounters with foragers returning with food. Because each forager searches until it finds food, this feedback from returning foragers links foraging activity to the amount of food: the more food is available, the shorter the search time, the more quickly foragers return, and the more foragers go out to search.

My long-term study of a population of harvester ant colonies has made it possible to learn how evolution is shaping their collective behavior. To understand how natural selection is currently acting, we needed to know whether the way that a colony regulates its foraging activity influences its ability to produce offspring colonies. The first step was to figure out which colonies were the offspring of which parent colonies. No one had ever made such a determination for ant colonies before. But since 1985 I have been following a population of about 300 colonies at a site in southeastern Arizona. Every year I find all the colonies that were there the year before, say good-bye to the ones that have died and put the newly founded colonies on a map. These long-term data show that a colony lives for 25 to 30 years. Each year there is a mating aggregation that brings together the males, which live only long enough to mate, and unmated queens, from all the colonies in the population. After mating, the males die, and the newly mated queens fly off to start new colonies. Each queen produces a new batch of sterile workers—and, once the colony is large enough, the fertile males and females—every year for the rest of her life, using the sperm she obtains at that original mating session. Based on DNA obtained from about 250 colonies, Krista Ingram of Colgate University, Anna Pilko of the University of California, San Diego, and I were able to link offspring colonies to their parent colonies and thus learn how a colony's foraging activity relates to its reproductive success.

We found that the colonies with offspring colonies tend to be those that conserve water by reducing foraging on hot, dry days, sacrificing food intake to conserve water. This result surprised us because many studies of animals assume that the more food they get, the better. But the colonies that for years I thought were unreliable and wimpy, because they do not forage much when it is hot and dry, turned out to be great-grandmothers, whereas our most stellar colonies, which forage steadily every day, had failed to reproduce. Because colonies can store seeds for a long time, there is no survival cost for not foraging on some days.

Natural selection operates on traits that can be passed from parent to offspring, and there is intriguing evidence for the heritability of collective behavior in harvester ants: offspring colonies resemble parent colonies in which days they choose to reduce foraging. Thus, our findings have provided what is, to my knowledge, the first demonstration of the current evolution of collective behavior in a wild population of animals.

ECOLOGICAL SOLUTIONS

DIFFERENT SPECIES OF ANTS show how the regime of interactions a species uses is related to its ecology. I also study turtle ants that live in the trees in the tropical forest of western Mexico. The air is very humid, and food is plentiful in the tropics, so operating costs of foraging are low there compared with the desert. But competition is high because many other ant species are exploiting the same resources. I found that turtle ant colonies create arboreal foraging trails along which ants perpetually circle from one nest or food source to another. Unlike harvester ants, turtle ant foragers keep going unless interactions lead them to stop or slow down. For example, interactions with ants of other species inhibit activity. A turtle ant is likely to leave the nest and to con-

IN BRIEF

Ant colonies work without a leader. They organize their activities using simple interactions based on scent.

The system of interactions that a colony uses is related to its ecology.

Insights into collective behavior in ants could illuminate other systems that operate without central control.

PRECEDING PAGES: ALEX WILD

tinue on the trail unless it meets an ant of another species. Just one *Pseudomyrmex* ant strutting back and forth on a branch, sleek and severe like a sports car, can meet enough of the stockier yet more timid turtle ants to completely shut down a branch of their trail. Colonies are so persistent in maintaining the flow of ants on a trail when all is clear, and starting it again once a threat disappears, that perhaps it is easiest to avoid conflict.

Simple interactions among ants create the turtle ant colony's network of trails within the tangled vegetation of the forest canopy. Those interactions make the network both resilient and flexible. Every ant marks its route with a chemical trail pheromone as it goes and follows the scent of the ants that came before it. Saket Navlakha of the Salk Institute for Biological Studies and I are working to understand the algorithm that the ants use to maintain and repair their trails. When an ant reaches a junction between one twig, stem or vine and another, it tends to take the path that smells the strongest of trail pheromone, which is the path most recently traveled by the most ants. Often a tenuous bridge between one stem and another falls away because of the wind, a passing lizard, a break in a rotting branch or, sometimes, an experimental intervention from my scissors. The ants recover quickly. It seems that when they reach the first broken edge, the ants go back to the next available node and search for the pheromone trail from there until they form and eventually prune a new path to join the other side of the path.

Collective behavior in ants has evolved in response to how resources such as food are distributed in the environment, as well as to the costs of foraging and the behavior of other species that they meet. Some resources are clustered together in a single patch, whereas others are scattered at random. Ants of many species excel at exploiting patchy resources such as picnics. They use interactions based on pheromones in which one ant follows another, producing recruitment trails. Recruitment makes sense when the resource is patchy—after all, where there are sandwiches, there are likely to be cookies. In contrast, ants that forage for scattered resources, like seeds, do not use recruitment trails, because finding one seed is no guarantee of finding another nearby.

To find food in the first place also requires specialized collective behavior. Because ants operate mostly by smell, an ant must get close to food to find it. The broader the range of places where food might be, the more area the ants must cover. But the more different places it could be tucked away, the more thoroughly searchers must scour the ground. I found that Argentine ants manage this trade-off beautifully, by adjusting their paths according to density. When there are few ants in a small space, each ant takes a convoluted path, allowing it to search the local area very thoroughly. But when there are few ants in a large space, they use straighter paths, which allows the entire group to cover more ground. Individuals could sense density by a simple cue: the rate of interactions with others. The more antennal contacts they make, the more convoluted a route they take. The Argentine ant has invaded Mediterranean climates throughout the world. Perhaps its effectiveness at getting to new food resources first explains why this invasive species tends to outcompete native species wherever it invades.

LESSONS FROM ANTS

THE WAYS ANTS USE simple interactions to thrive in particular environments could suggest solutions to problems that arise in other systems. Computer scientist Balaji Prabhakar of Stanford University and I noticed that the harvester ants use an algorithm to regulate foraging that is similar to the transition-control protocol/Internet protocol (TCP/IP) used in the Internet to regulate data traffic. We called the analogy the "Anternet." TCP-IP was designed in an environment with high operating costs: the early Internet was so small that there was little redundancy, and ensuring that no data packet would be lost was crucial. Just as a forager will not leave on its next trip unless it has a sufficient number of interactions with returning foragers that have found food, so a data packet will not leave the source computer unless it receives an acknowledgment from the router that the previous packet had the bandwidth to travel on toward its destination. It seems likely that 130 million years of ant evolution have produced many other useful algorithms that humans have not yet thought of and that could help us figure out ways to organize data networks using simple interactions involving minimal information.

I think that we will probably see a similar fit between algorithm and ecological situation in many other kinds of collective behavior. For example, cancers evolve in response to the conditions in their local microenvironment. A type of cancer that tends to metastasize to a particular kind of tissue probably evolves to use resources clustered in that tissue. These forms of cancer, like the species of ants that have evolved to use patchy resources, may be the most likely to send cells back to the primary tumor to recruit more cells, as breast cancer cells do. In that case, cells that recruit to patchy resources would be the best target for poison baits.

Throughout biology and engineering there is an explosion of interest in how collective behavior draws on simple interactions. It is becoming clear that such interactions are tuned to changing conditions. The field of systems biology, building on a century of work that showed in detail what happens inside a cell, is shifting its focus to interactions among cells, aided by amazing advances in imaging. In neuroscience, new techniques allow recordings that show patterns in the timing of thousands of neurons firing. We humans can see certain kinds of movement and hear certain sounds because circuits of neurons in our brains have evolved to respond collectively to features of the environment such as the rate at which crucial objects, such as parents and predators, usually move, and to the range of frequencies that it was most important to be able to hear. Engineered systems evolve as well; enormous increases in the size of the Internet and the number of devices connected to it, as well as the speed of interactions, require new, decentralized solutions.

Scientists are now ready to look for trends in the ways that different natural systems have evolved similar collective behavior to meet similar ecological challenges. We may be able to apply that knowledge to intervene in processes that work without central control—and solve some of society's problems in the process. SA

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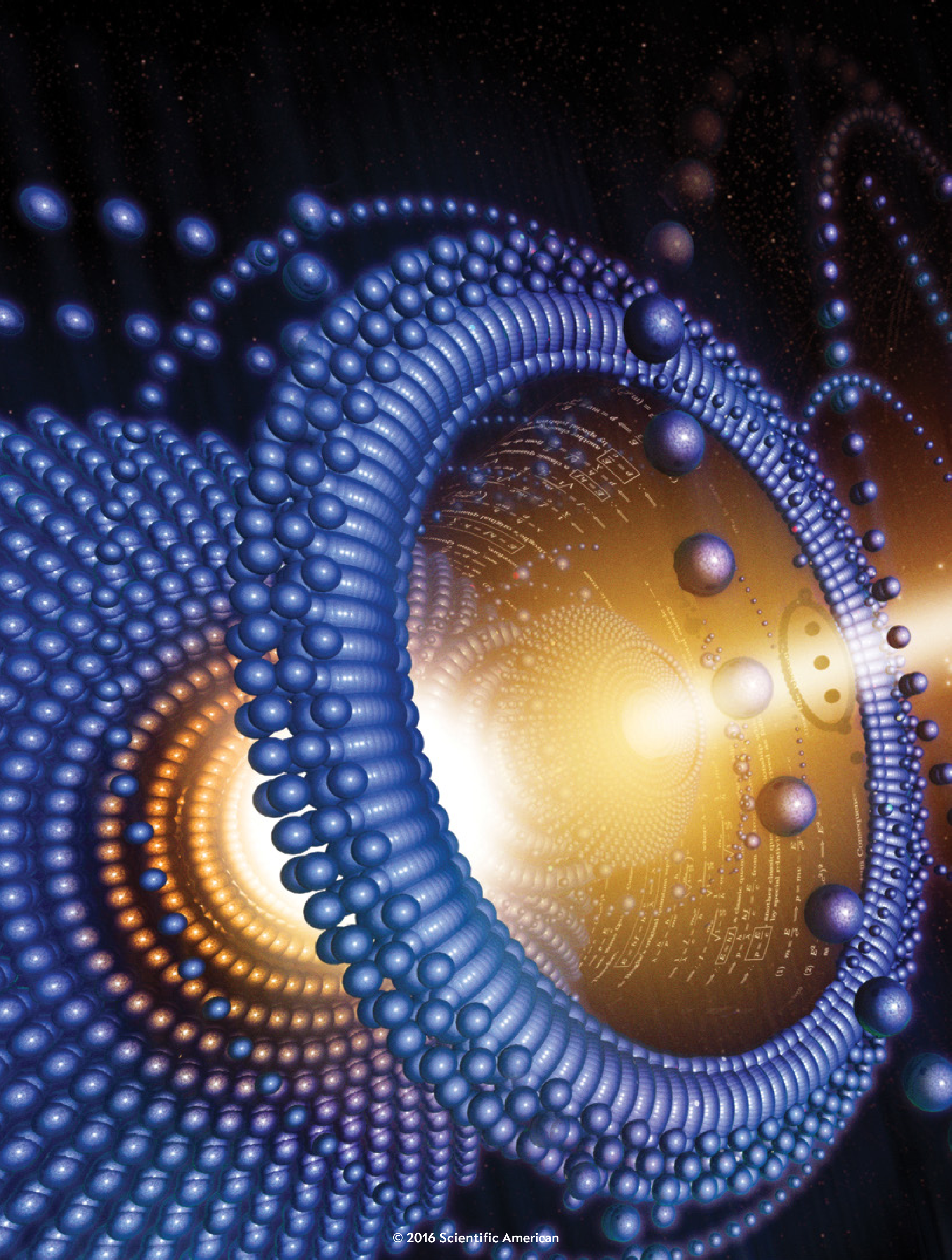
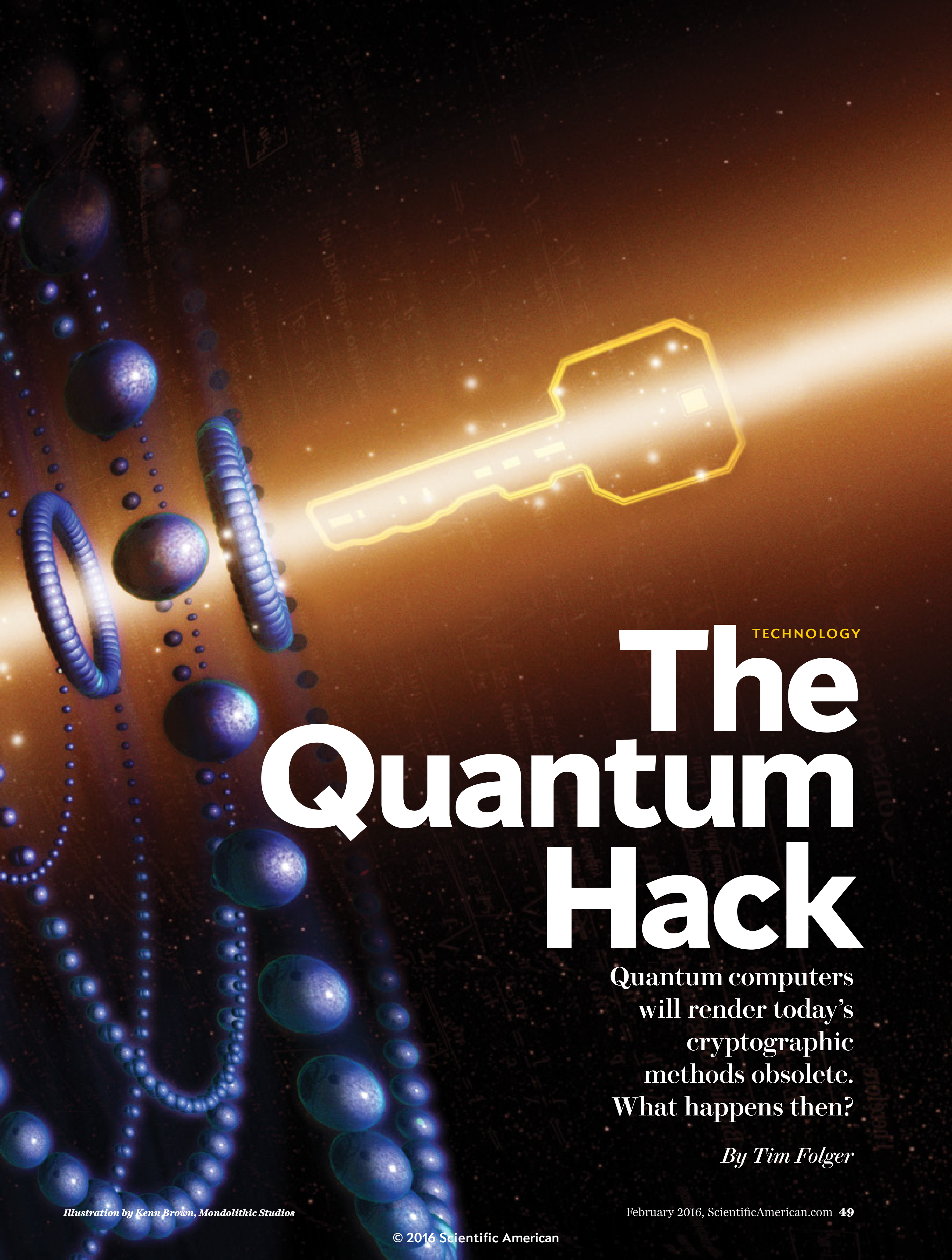




TECHNOLOGY

The Quantum Hack

Quantum computers will render today's cryptographic methods obsolete. What happens then?

By Tim Folger

Illustration by Kenn Brown, Mondolithic Studios

Tim Folger writes for *National Geographic*, *Discover* and other national publications. He is also the series editor for *The Best American Science and Nature Writing*, an annual anthology published by Houghton Mifflin Harcourt.

ONE BRIGHT OCTOBER AFTERNOON ON A BEACH IN SAN JUAN, PUERTO RICO, two scientists found the solution to a problem that didn't yet exist. It was 1979. Gilles Brassard, then a newly graduated Ph.D. from Cornell University, was immersed in the warm Caribbean water when someone swam toward him. The dark-haired stranger launched into a pitch about how to make a currency that could not be counterfeited. The scheme, invented several years earlier by a Columbia University graduate student named Stephen Wiesner, involved embedding photons—particles of light—in banknotes. By the laws of quantum mechanics, any attempt to measure or copy the photons would instantaneously change their properties. Each bill would have its own string of photons, a quantum serial number that could never be duplicated.

"I was surprised, of course," says Brassard, now a professor of information science at the University of Montreal, "but I listened politely." The conversation, he says, turned out to be a life-changing experience. His new acquaintance was Charles Bennett, a research physicist at IBM. Bennett had recognized Brassard from a conference they were attending. Although they were both intrigued by the quantum-banknote idea, they knew it was technically infeasible. Even today no one knows how to capture, immobilize and store photons in a piece of paper. Light particles, after all, tend to move rather quickly.

"We're better now but still nowhere close to anything that would be remotely practical for quantum banknotes," Brassard says. "But it was a starting point as a thought experiment. It's a beautiful example of an idea that is completely ridiculous in terms of being practical but at the same time turns out to be totally seminal. Because it was from there that Bennett and I had the idea for what is now known as quantum-key distribution."

Quantum-key distribution, or QKD, is a technique to encode and transmit data using photons. In principle, it provides a completely unbreakable form of cryptography. After that day on the beach, Bennett and Brassard began a five-year collaboration that produced the first cryptographic method in history to rely not on mathematical complexity but on the laws of physics. When Bennett and Brassard finally published their work in 1984, few researchers took the idea seriously or even noticed it. "It was considered a fringe pursuit," Brassard says. "And that was for those who paid any attention. I don't think we took ourselves very seriously either."

That is no longer the case. Thirty years ago hardly anyone outside of government intelligence agencies used cryptographic technology. Now it has become essential to routine transactions on the Internet. Whenever someone enters a password or credit-card number online, sophisticated programs built into all Web browsers work behind the scenes to keep that information safe from cyberthieves. "This is a technology that everyone needs but that no one is aware of," says Vadim Makarov, a researcher at the Institute for Quantum Computing at the University of Waterloo in Ontario. "It just works."

But it might not work for much longer. Nearly every encryption scheme now in use is likely to become obsolete with the advent of quantum computers—machines capable of cracking the elaborate codes that protect everything from Amazon purchases to power grids. Although no one has yet built a full-blown quantum computer, researchers in academic, corporate and government laboratories around the world are trying. Among the documents released by whistle-blower Edward Snowden was a description of a secret National Security Agency project called

IN BRIEF

Conventional computers have been ill equipped to crack the encryption schemes, often based on large prime numbers, at the core of everyday online commerce and communication.

Quantum computers, however, could break today's encryption schemes by exploiting the strange rules of the subatomic world and trying all solutions to a code simultaneously.

No one has built a full-scale quantum computer, but academic, government and private researchers are trying, and some experts say they could succeed in as little as 10 years.

That is why researchers are racing to perfect and deploy technology for quantum encryption, which uses quantum uncertainty to create nearly unbreakable codes.

Penetrating Hard Targets—a $79.7-million effort to build a quantum computer. "It's hard to say with any confidence that one won't exist in 10 or 15 years," says Ray Newell, a physicist at Los Alamos National Laboratory.

If or when that first quantum computer boots up, the most effective counter to its code-breaking powers may turn out to be another kind of quantum wizardry: cryptographic networking technology based on the theory Bennett and Brassard devised 32 years ago. Quantum encryption—a method of encoding transmissions that exploits the strange properties of single particles of light—has, it turns out, been an easier problem than building a quantum computer. Indeed, some small quantum-encryption projects are already up and running. There is just one problem: replacing the world's encryption systems with quantum versions will probably take longer than developing quantum computers. "If you think this problem might exist in 10 to 15 years, we need to be doing this *yesterday,*" Newell says. "We're probably already too late."

VERY BIG NUMBERS

HIDDEN BEHIND THE EFFORTLESS mouse clicks and screen taps of Web commerce stands an elegant and complex mathematical scaffolding of two distinct forms of cryptography: symmetric encryption, in which the same secret key is used to encrypt and decrypt data, and asymmetric encryption, in which one key encodes the message and a different key deciphers it. Every exchange of secure information on the Internet requires both methods.

A typical session between someone's home computer and an online retailer's Web server starts with the creation of a symmetric key that the customer and merchant will share over the Internet to encode credit-card numbers and other private information. A key is essentially a set of instructions for how to encode information. A ridiculously simple key might specify that every digit in a credit-card number be multiplied by three. In the real world, of course, keys are far more complex mathematically. Whenever someone purchases something on the Internet, the Web browser on the home computer exchanges a key with the server of the online retailer. But how is the key itself kept private during that initial exchange? A second layer of security—an asymmetric one—encrypts the symmetric key.

Invented independently in the 1970s by the British secret service and academic researchers, asymmetric encryption uses two different keys: a public key and a private key. Both are necessary for any encrypted transaction. During an online purchase, a merchant's server sends its public key to a customer's computer. The customer's computer then uses the merchant's public key—which is openly available to all customers—to encrypt a shared symmetric key. After receiving the encrypted symmetric key from a customer, the merchant's server decrypts it with a private key, which no one else possesses. Once the symmetric key is safely shared, it encrypts the rest of the transaction.

The public and private keys used in asymmetric encryption are derived from the factors of very large numbers—specifically, prime numbers, integers divisible only by 1 and themselves. The public key consists of a number generated by multiplying two

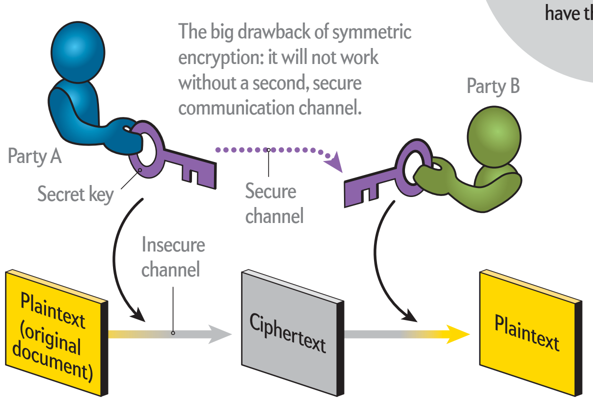
TODAY

How Encryption Works—for Now

Every time you buy something online, your browser and the seller's Web site exchange a secret code—a key for encrypting the information they are about to exchange. Because both parties use the same key, this process is known as symmetric encryption. To securely share that key, however, both parties rely on a second form of encryption—asymmetric encryption. This two-step system works well, but if working quantum computers arrive, it could become instantly obsolete.

Symmetric Encryption

Faced with an insecure communication channel, Party A encodes a message before sending it to Party B over an insecure channel. If someone intercepts the message, no problem: the encoded message will be gibberish. Party B, however, *can* read the message because Party A has sent Party B a secret key through a secure back channel.

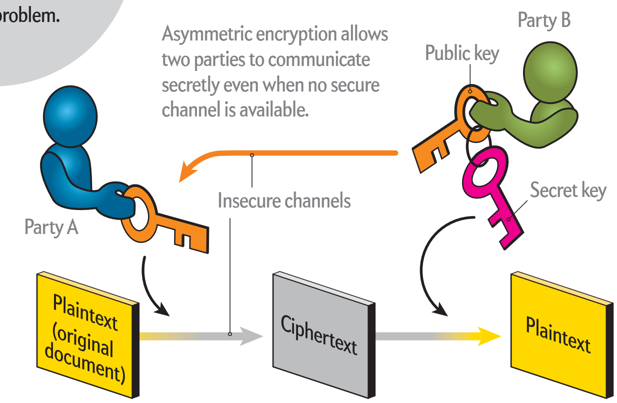


Vulnerabilities

Asymmetric encryption works because it is extremely difficult for classical computers to factor very large numbers. Quantum computers do not have this problem.

Asymmetric Encryption

Party B—the recipient—selects a pair of keys: one that explains how to encode a message and one that explains how to decode it. Party B publishes instructions for encoding messages. This is the "public" key. Party A encodes her messages according to the public key. When Party B gets the encoded message, she decodes it using the second, secret key.



Illustrations by Jen Christiansen

large prime numbers together; the private key comprises the two prime factors that create the public key. Even children can multiply two primes, but the reverse operation—splitting a large number into two primes—taxes even the most powerful computers. The numbers used in asymmetric encryption are typically hundreds of digits long. Finding the prime factors of such a large number is like trying to unmix the colors in a can of paint, Newell says: "Mixing paint is trivial. Separating paint isn't."

The most widely used asymmetric encryption method is known as RSA, after its creators: Ron Rivest, Adi Shamir and Leonard Adleman, who developed the idea in the late 1970s at the Massachusetts Institute of Technology. Key lengths have been increasing steadily to keep them safe from hackers with faster computers and better skills; longer keys require more computing power to break. Asymmetric keys now are typically 1,024 bits long, but even leaving aside the prospect of quantum computers, that might not be enough to foil future cyberattacks. "The National Institute of Standards and Technology is actively recommending that RSA key sizes be upgraded to 2,048 bits," says Richard Hughes, a physicist at Los Alamos. "But the increase in key size comes at a performance cost. That annoying time lag when you click 'purchase' and things hang for a moment or two—that's the public-key cryptography working. And the bigger the key size, the longer the time delay." The problem is that the processors in our computers are not improving quickly enough to keep up with the decrypting algorithms that are driving the need for increasingly long keys. "That gets to be a concern for a lot of reasons," Hughes says. "If you're running a cloud system with many public-key sessions at once or if you're running something like the electric grid, you just can't have that kind of time lag."

Even NIST's recommended upgrade will become obsolete if quantum computers come on the scene. "I think there's a one-in-two chance that a quantum computer will be able to break RSA-2048 by 2030," says Michele Mosca, co-founder of the Institute for Quantum Computing, in reference to RSA's forthcoming 2,048-bit keys. "We've certainly seen a lot of advances in the past five years that lead us to think we need to be prepared in case we do see quantum computers," says Donna Dodson, chief cybersecurity adviser for NIST. "We're of the mind-set that they're probable."

OF CODES AND QUBITS

WHY WOULD A QUANTUM computer be so powerful? In a conventional computer, any single bit of information can assume only one of two values: 0 or 1. A quantum computer, however, takes advantage of a weird property of the subatomic world, where individual particles can exist in many states at once. Like Erwin Schrödinger's cat in a box—existing both alive and dead until someone opens the box for a look—a quantum bit, or qubit, of information can be a 1 and a 0 at the same time. (Physically, a qubit might be a single electron held in two spin states simultaneously.) A quantum computer with 1,000 qubits would contain $2^{1,000}$ different possible quantum states, exceeding by far the total number of particles in the universe. That does not mean a quantum computer could store limitless amounts of data: any attempt to observe the qubits would immediately cause them to assume a single 1,000-bit value. Yet with clever programming, the vast number of possible qubit states could be harnessed while *unobserved* to perform calculations that are impossible with conventional computers.

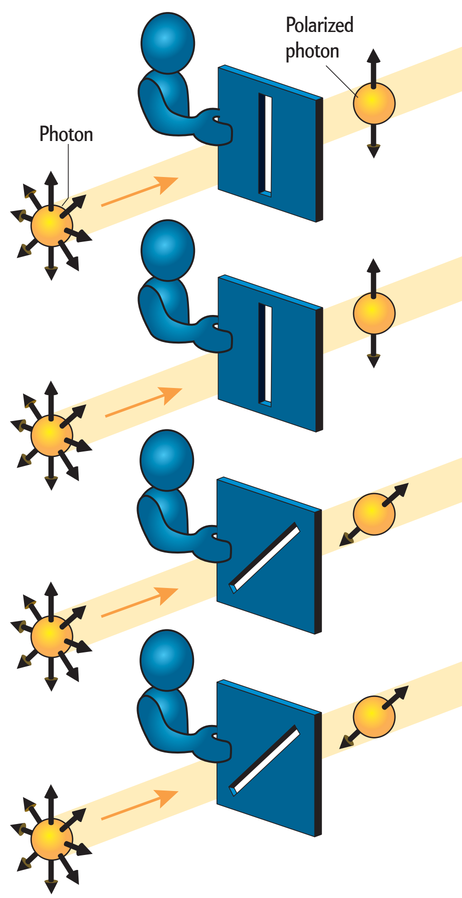
In 1994 Peter Shor, a mathematician then at AT&T Bell Laboratories, proved that a quantum computer could factor the kinds of large numbers that are used in RSA encryption—the asymmetric encoding scheme that protects the exchange of symmetric keys during Internet transactions. In effect, Shor wrote the first program for a quantum computer. Unlike a normal computer, where calculations proceed sequentially, one step at a time, a quantum computer performs all its operations simultaneously, a property Shor exploited. "Shor's algorithm would shatter RSA," Mosca says. But symmetric encryption methods—the most common being the Advanced Encryption Standard (AES), approved by NIST in 2001—would still be safe from quantum computers. That is because symmetric encryption programs such as AES do not use prime numbers to encode keys. Instead symmetric keys

TOMORROW

The Quantum Future of Cryptography

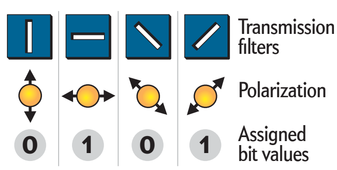
Quantum-key distribution is a way of securely sharing a cryptographic key using a stream of light particles, or photons, that are polarized. If an eavesdropper measures those photons while they are in transit, the act of measurement will change the polarization of some of those photons, and the sender and recipient will know that their message has been tampered with.

Transmitter has four polarizing filters. Each bit (as encoded by the photon's orientation) is recorded as it is transmitted.



Sending and Receiving Polarized Photons

The sender (*blue*) transmits a series of photons; each passes through one of four polarizing filters. Each filter—and therefore polarization direction—is assigned a bit value of 0 or 1 (*below*). The sender writes down the bit value of each photon. The recipient (*green*) can only determine the bit value of each photon after it has passed through a receiving filter.



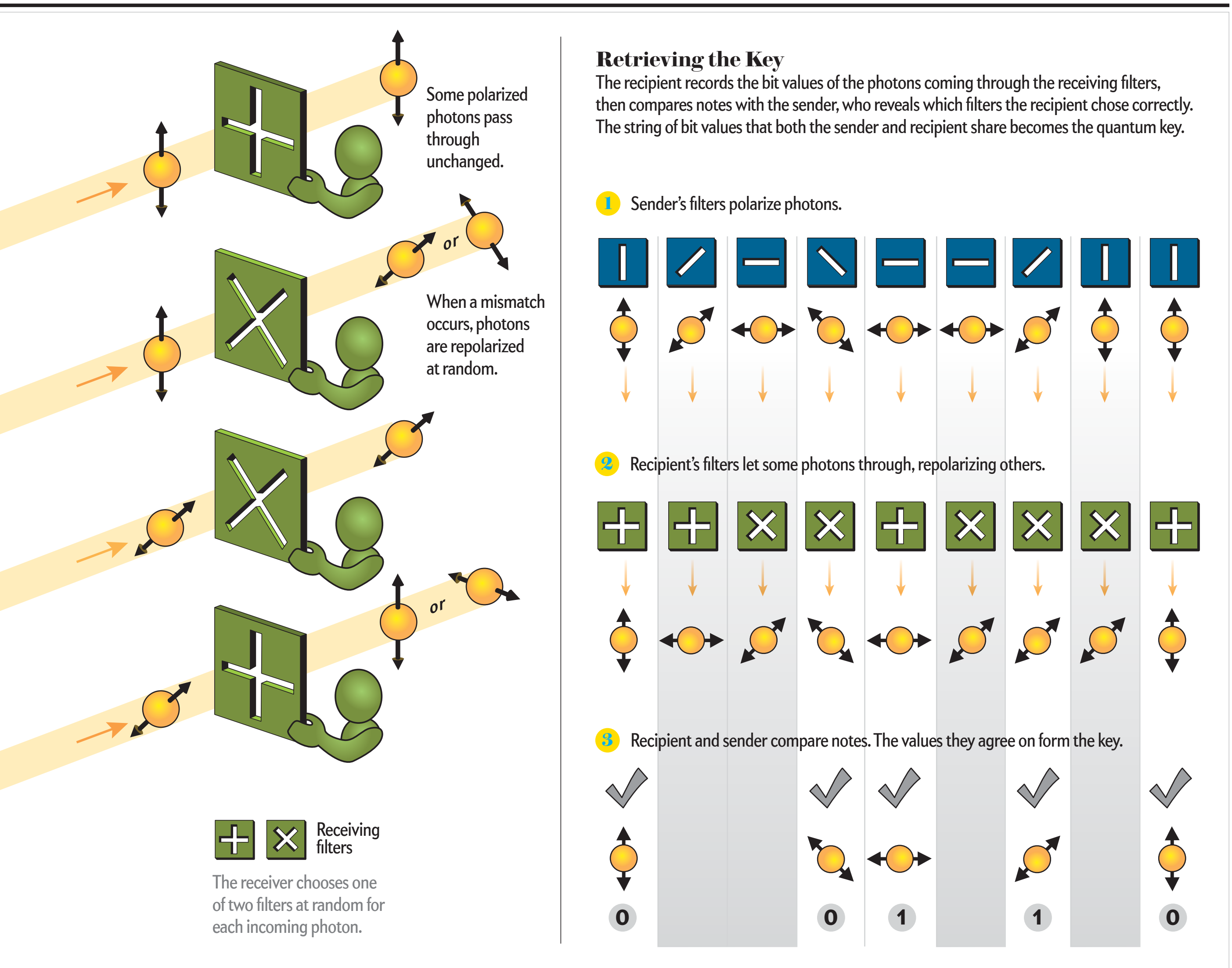
consist of randomly generated strings of 0s and 1s, typically 128 bits long. That makes for 2^{128} different possible key choices, which means a hacker would have to sort through some billion billion billion billion key combinations. The world's fastest computer—China's Tianhe-2, which can blaze through 33.8 quadrillion calculations per second—would need more than a trillion years to search all the key options. Even a quantum computer would not help hackers *directly* crack such huge numbers. But again, those enormous *symmetric* keys are encrypted during Internet transactions with *asymmetric* programs such as RSA, which *are* vulnerable to Shor's factoring method.

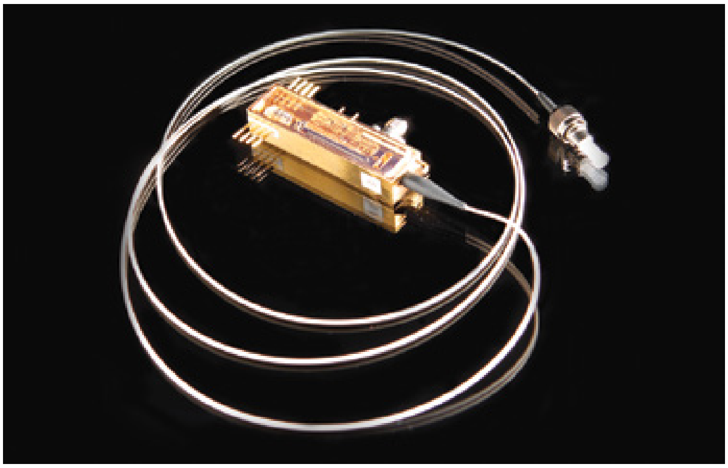
Before Shor's program can dismantle RSA, though, it first needs a quantum computer of sufficient power on which to run. Within the next year Mosca predicts that a number of labs around the world will have developed rudimentary systems consisting of a few tens of qubits. "If you're trying to factor a 2,048-bit RSA key," he says, "you probably need at least 2,000 qubits." The leap from tens of qubits to thousands might take a decade, but he sees no insurmountable obstacles. "Right now we meet most of the performance criteria to build a large-scale quantum computer," he says, "just not necessarily in the same place at the same time in a system that can be made larger."

QUANTUM NETWORKING

THE GOOD NEWS is that so far progress in quantum-encryption technology has outstripped efforts to build a working quantum computer. Quantum encryption began to take off in 1991, when Artur Ekert, a physicist at the University of Oxford, published a paper on quantum cryptography in the prestigious *Physical Review Letters*. Ekert, who at the time was unaware of the earlier work by Bennett and Brassard, described an alternative method of using quantum mechanics to encrypt information. His work eventually brought new recognition to Bennett and Brassard's idea, which turned out to be more practical than Ekert's own scheme.

It was not until the early 2000s, however, that quantum-encryption technology began to move out of the lab and into the commercial world. By then, physicists had found ways to cool photon detectors—the essential and most expensive component of any quantum-encryption device—using electric currents instead of liquid nitrogen. "When I started my Ph.D. in 1997, you cooled them





QUANTUM ROUTER: The QKarD, developed by researchers at Los Alamos National Laboratory, would allow any number of computers, cell phones and other gadgets to exchange quantum keys through a secure, central server.

COURTESY OF LOS ALAMOS NATIONAL LABORATORY

by dipping the detectors into a dewar of liquid nitrogen, which is okay in the lab but not very practical if you want to use them in a data center," says Grégoire Ribordy, CEO of ID Quantique, a Swiss firm that in 2007 developed one of the first commercial quantum-encryption systems, which the Swiss government bought to protect data centers. The company has since sold its wares to Swiss banks and is now working with Battelle Memorial Institute in Columbus, Ohio, to build a network that will eventually link the company's Ohio offices with a branch in Washington, D.C.

On an overcast summer day Nino Walenta, a physicist at Battelle, shows me one of the encryption devices. "All we need is on this shelf," he says. "All the quantum optics, and everything we need to generate keys and distribute them, is right here." Walenta is standing next to a two-meter-high cabinet in a basement lab at Battelle's Columbus facility. On one shelf of the cabinet is a metal box about the size of a large briefcase. Within it lies the physical realization of the quantum-coding scheme first proposed by Bennett and Brassard more than three decades ago.

The hardware consists of a small laser diode, similar to those used in DVD players and bar-code scanners, that aims pulses of light at a glass filter. The filter absorbs nearly all the photons, allowing, on average, the passage of only a single particle of light at a time. Those individual photons are then polarized in one of two directions, each direction corresponding to a bit value of 1 or 0. Once filtered and polarized, the photons become the basis for a secret key that is then transmitted along a fiber-optic cable to the intended recipient, whose own hardware decodes the key by measuring the photons' polarizations.

Unlike a conventional secret key, the photon key is nearly tamper-proof. (More on that "nearly" in a bit.) Any eavesdropper who tries to intercept the photons will disturb them, altering their values. By comparing parts of the key, the legitimate sender and receiver can check whether the transmitted photons match the originals. If they detect signs of spying, they can scrap the key and start again. "Today keys are often used for years," Walenta says. "But with quantum-key distribution, we can change the key every second or every minute, which is why it is so secure."

Battelle has already set up a quantum network to exchange financial reports and other sensitive material between its Columbus headquarters and one of its manufacturing facilities in Dublin, Ohio, with a 110-kilometer loop of fibers connecting them. That distance, it turns out, approaches the upper limit for sending quantum-encrypted messages. Beyond that, the signal deteriorates because of the absorption of photons by the fiber-optic cable.

To get around that limitation and extend their network to cover more of Columbus—and, in the near future, to cover Washington, D.C.—the researchers at Battelle are working with ID Quantique to deploy "trusted nodes," relay boxes that receive and resend quantum transmissions. The nodes would be encased in sealed, insulated units to protect the sensitive photon detectors inside, which are cooled to –40 Celsius. If someone tried to break into one of the nodes, the device inside would shut down and erase itself. "Key generation would stop," says Don Hayford, a physicist who directs quantum-encryption research at Battelle.

If the chain of trusted nodes works smoothly, Hayford says, the technology could be deployed on a larger scale. He hands me a brochure with a map illustrating a future quantum network extending across large parts of the country. "That is our vision of a quantum network that protects all the Federal Reserve banking systems," he says. "If you get all the Federal Reserve banks, you've done pretty well. To go across country, you would need 75 nodes, roughly, which sounds like a lot, but when you do any conventional fiber networking, you have repeaters at about the same intervals."

The Chinese government has embraced similar technology. Construction has begun on a 2,000-kilometer quantum network between Shanghai and Beijing for use by the government and financial institutions. Whereas the projects envisioned by Hayford and under way in China might be used to protect banks and other organizations with private networks, they would not be practical for the Internet. The trusted nodes link one computer to the next in a linear chain rather than in a branching network where any machine can easily communicate with another. To Beth Nordholt, a physicist who recently retired from Los Alamos, such point-to-point connections recall the chaotic beginnings of the telephone industry in the late 19th century, when dark thickets of cables overhung city streets. "In those days you had to have a separate wire for everybody you wanted to talk to," she says. "That doesn't scale well."

Nordholt and her husband, Richard Hughes, and their Los Alamos colleagues Newell and Glen Peterson are working to make quantum encryption more scalable. For that purpose, they have built a device about the size of a memory stick that would allow any number of networked gadgets—cell phones, home computers or even televisions—to exchange quantum keys by connecting to a secure, centralized server. They call their invention the QKarD, a play on quantum-key distribution.

"The expensive parts of quantum cryptography are the single photon detectors and all the things to cool them and make them happy," Nordholt says. So she and her colleagues placed the complicated, costly components in one computer at the hub of a network. Client computers, each equipped with a QKarD, connect to

SCIENTIFIC AMERICAN ONLINE For more on the quantum-encryption race, go to ScientificAmerican.com/feb2016/crypto

the hub—but not directly to one another—by fiber-optic cables. The QKarD itself is a transmitter, with a small laser that allows it to send photons to the hub.

The QKarD works something like a telephone switchboard. Each computer on the network uploads its own symmetric keys encoded as streams of photons to the hub. This quantum encryption replaces the RSA encoding that would typically be used to protect the transmission of symmetric keys. Once the keys have been exchanged between the various client computers and the hub, the hub uses the keys and AES to relay conventional, nonquantum messages among any clients in the network that need to share sensitive data.

Nordholt's team has been running a model QKarD. Even though the entire system sits in one small lab at Los Alamos, a 50-kilometer length of fiber-optic cable, spooled in a bucket underneath a lab bench, connects the system's components and simulates real-world distances. The QKarD technology has been licensed for commercial development to Whitewood Encryption Systems. If the device does make it to market, Hughes estimates that a central hub capable of linking 1,000 QKarD-equipped clients might cost $10,000. If mass-produced, the QKarDs themselves could sell for as little as $50.

"I would like to see a QKarD built into phones or tablets so you can have a secure connection to a server," Nordholt says. "Or you could put one in a base station in your office and upload keys [to a server]. You could organically build out networks."

A QUANTUM FUTURE?

OVERHAULING THE WORLD'S encryption infrastructure could take more than a decade. "The more broadly deployed something is, the harder it is to fix," Mosca says. "Even if we could fix this at a technological level, everyone would have to agree on how to do this and have it all be interoperable for one global telecommunications system. We don't even have a common electrical system—we have to get adapters every time we travel."

The very difficulty of the challenge only adds to the urgency, Nordholt says: "This isn't just about protecting credit-card numbers. It's getting really serious." A few years ago, she says, Idaho National Laboratory conducted a study showing that hackers could blow up generators by feeding bad data into the networks that control the power grid. "I don't want to bring up doomsday scenarios," she says, "but this makes a real difference in people's lives."

The first target of a quantum computer, though, probably will not be a power grid. Many researchers in the field of cryptography believe that the NSA and other intelligence agencies around the world are storing huge quantities of encrypted data from the Internet that cannot be cracked with today's technology. The data are being saved, the reasoning goes, with the expectation that the NSA will be able to decrypt them when the agency has a quantum computer. In that scenario, it will not be only the private transactions of citizens a few decades from now that are at risk. It will be our own communications from today—communications that we naively consider to be secure.

"It would be completely crazy to think that there is not someone—maybe many someones—out there taking down all the traffic, just waiting for the technology to break it all retroactively," Brassard says. "So even if a quantum computer is not yet available, and even if one is not developed for the next 20 years, as soon as one *is* available, all the traffic that you've sent from day one of using these classical [encryption] techniques is compromised."

And even when widespread quantum encryption arrives, the cat-and-mouse game of encryption will continue. If the history of conventional cryptography is any guide, there is inevitably a gap between theoretical perfection and real-world implementation. When RSA encryption was first introduced, it was considered completely secure, says Zulfikar Ramzan, chief technology officer of RSA, the company that Rivest, Shamir and Adleman created to commercialize their invention. But in 1995 then Stanford University undergraduate Paul Kocher discovered that he could crack RSA's encryption simply by observing how long it took a computer to encode a small amount of data.

"It turns out that if the key has more 1s than 0s, it takes a bit more time to compute an RSA encryption," Ramzan says. "And then repeating that observation over and over again and measuring the timing, you can actually derive the entire RSA key, purely by looking at the amount of time the computation took." The work-around was fairly simple—engineers managed to camouflage the calculation times by adding some randomness to the procedure. "But again, it was the kind of attack that nobody conceived of until someone came up with it," Ramzan says. "So there may be similar attacks within the context of quantum computing."

In fact, the first quantum hack attack has already occurred. Five years ago a team led by Makarov, then at the Norwegian University of Science and Technology, connected a suitcase packed with optical equipment to a fiber-optic communications line linked to a quantum-encryption system built by ID Quantique. By using laser pulses to temporarily blind the encryption device's photon detectors, Makarov's team was able to successfully decrypt a supposedly secure quantum transmission.

Such an attack would be beyond the reach of an ordinary hacker, Makarov says. "You need to be a bit older than a teenager," he says. "And you need to have access to an optic lab. You don't have this technology in basements—yet." Although ID Quantique has since patched its device so that it is no longer vulnerable to the same type of attack, Makarov's successful hack popped the bubble of invincibility that surrounded quantum cryptography. "Breaking is easier than building," he says.

For Brassard, there is no doubt that the crackpot idea he and Bennett hatched on a beach all those years ago—even if it is imperfect—will be crucial to the future security of the world's many networks. "It requires the will to do it," Brassard says. "It will be expensive, just like fighting climate change will be expensive. But it's an expense that is minuscule compared to what will be lost if we don't do it—in both cases." SA

MORE TO EXPLORE

The Cost of the "S" in HTTPS. David Naylor et al. in *Proceedings of the 10th ACM International on Conference on Emerging Networking Experiments and Technologies*, pages 133-140; 2014.

NSA Seeks to Build Quantum Computer That Could Crack Most Types of Encryption. Steven Rich and Barton Gellman in *Washington Post;* January 2, 2014.

FROM OUR ARCHIVES

Quantum Cryptography. Charles H. Bennett, Gilles Brassard and Artur K. Ekert; October 1992.

Best-Kept Secrets. Gary Stix; January 2005.

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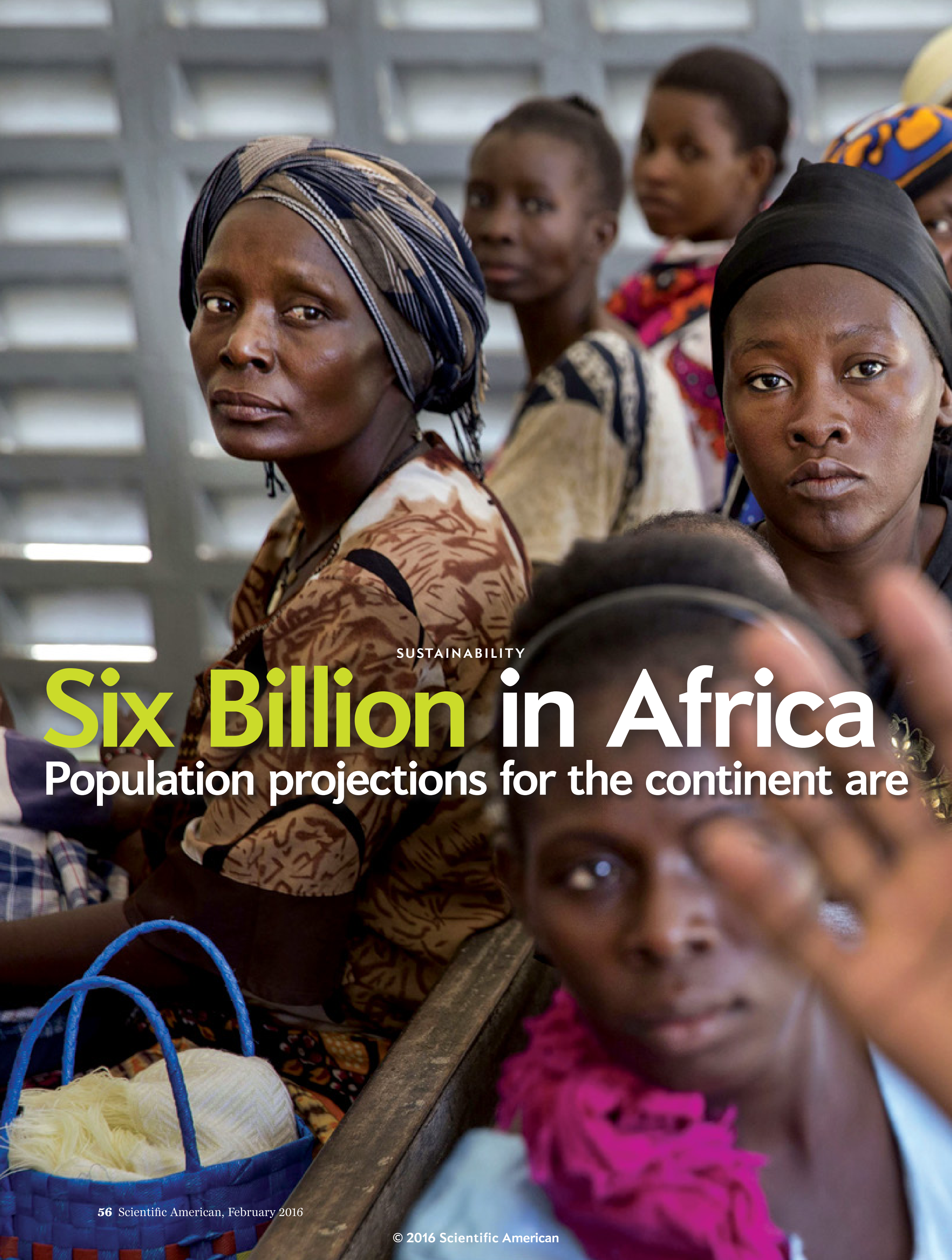


SUSTAINABILITY

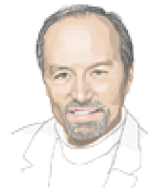
Six Billion in Africa

Population projections for the continent are

alarming. The solution: empower women

By Robert Engelman

COUNSELOR from Marie Stopes International educates women gathered at a hospital in Rabai, Kenya, about family-planning options, including emergency contraception.



Robert Engelman directs research on connections between family planning and environmental sustainability at the Worldwatch Institute, where he was formerly president. For many years he reported on health, science and the environment for U.S. newspapers. His book, *More: Population, Nature, and What Women Want* (Island Press), won the Population Institute's Global Media Award in 2008.

EARTH IS A FINITE PLACE. THE MORE PEOPLE WHO inhabit it, the more they must compete for its resources. Although human population has grown steadily, developments in recent decades have been encouraging. Globally, women today give birth to an average of 2.5 children, half as many as in the early 1950s. In 40 percent of the world's nations, the fertility rate is at or below the "replacement" level of 2.1 children per woman, the number at which offspring simply take the place of their parents.

Then there is Africa, where women give birth on average to 4.7 children and the population is rising nearly three times faster than in the rest of civilization. The continent where our species arose faces a worrisome future. Fertility—the number of live births over a woman's lifetime—remains high in most of Africa's 54 countries. Africans have long valued large families as a matter of status and as a way to create family workers for farmland and to counteract high death rates for young children. And more babies than ever are surviving to become parents themselves. More than half the continent's nearly 1.2 billion people are children or teenagers, a ratio that is building powerful momentum for years of expansion at a pace humanity has never known. By the end of this century, demographers now project, Africa's inhabitants will triple or quadruple.

For years the prevailing projections put Africa's population at around two billion in 2100. Those models assumed that fertility rates would fall fairly rapidly and consistently. Instead the rates have dropped slowly and only in fits and starts. The United Nations now forecasts three billion to 6.1 billion people—staggering numbers. Even conservative estimates, from places such as the International Institute for Applied Systems Analysis in Austria, now see Africa at 2.6 billion. The U.N. has in recent years continually raised its midline projection for 2100 world population, from 9.1 billion in a 2004 estimate to 11.2 billion today. Almost all of the unanticipated increase comes from Africa.

Extreme growth threatens Africa's development and stability. Many of its inhabitants live in countries that are not especially well endowed with fertile soils, abundant water or smoothly functioning governments. Mounting competition for nourishment and jobs in such places could cause strife across the region and, in turn, put significant pressure on food, water and natural resources around the world, especially if Africans leave their nations in droves, which is already happening. As many as 37 percent of young adults in sub-Saharan Africa say they want to move to another country, mostly because of a lack of employment.

Africa needs a new approach to slowing its population rise, to preserve peace and security, improve economic development and protect environmental sustainability. And the world needs to support such efforts. From the 1960s to 1990s, international foundations and aid agencies urged African governments to "do something" about escalating population growth. That "something" usually amounted to investing in family-planning programs without integrating them with other health care services, plus making government statements that "smaller is better" for family size. From the mid-1990s onward, however, silence descended. Calling population growth a problem was seen as culturally insensitive and politically controversial. International donors shifted their focus to promoting general health care reform—including fighting HIV/AIDS and other deadly diseases.

Africa and the rest of the world have to resurrect a sense of urgency. We need to get over our fear of the "P" word and jump-start multiple, coordinated steps that can nudge down the population-growth trajectory—in Africa and elsewhere where it is rising unsustainably. Research shows that beyond making sure women have access to effective contraceptives and the knowl-

IN BRIEF

By 2100 Africa's population could be three billion to 6.1 billion, up sharply from 1.2 billion today, if birth rates remain stubbornly high. This unexpected rise will stress already fragile resources in Africa and around the world.

A significant fertility decline can be achieved only if women are empowered educationally, economically, socially and politically. They must also be given easy and affordable access to contraceptives. Following this integrated strategy, Mauritius has lowered its fertility rate from six to 1.5 children; Tunisia's rate dropped from seven to two.

Men also have to relinquish sole control over the decision to have children and refrain from abusing wives or partners who seek birth control.

For such efforts to succeed ultimately, government leaders must encourage public and policy conversations about slower population growth.

JONATHAN TORGOVNIK *Getty Images (all photographs)* edge to use them, the best steps are the ones that make sense for other worthwhile reasons: educating girls and women and equalizing their social and legal status to those of men. Although a few countries have taken some of these actions in isolation, a far more effective approach would be integrating opportunities for women: educationally, economically, socially and politically.

Population can never be "controlled"—that would violate fundamental human rights and probably still would not work. But population can be influenced, indirectly yet powerfully. A smart suite of strategies can ease pressure on resources, reduce conflict, and make life more worthwhile for girls, boys, women and men.

Now imagine what Africa might look like with two billion people, much less six billion. History offers little guide. Asia surpassed four billion people in 2007, but it has 50 percent more land and considerably higher levels of economic development on average. Yet even with its assets, large swaths of that continent still face impoverished cropland, falling water tables, food insecurity and crippling air pollution.

One huge change in Africa will be a mushrooming of gigantic cities. The continent is urbanizing rapidly, with most people arriving from failed farmlands and settling into slums, scratching out what shelter and livelihoods they can. Metropolitan areas house nearly half a billion people today; by 2050 they would hold

AFRICA TODAY AND TOMORROW

MANY MEASURES CONFIRM that Africa's situation is already bleak. Despite economic progress and democratic advances, the continent stands out today for its low life expectancies, slow pace of development, and high rates of poverty and malnutrition. Crop yields are among the world's lowest. South of the Sahara, overgrazing by domestic animals encourages the desert to advance, pushing nomadic herders into the territory of farmers, as the populations of both groups grow. Egypt and Ethiopia have rattled sabers over the waters of the Nile, once shared effortlessly within the 11-nation river basin; a 2010 analysis found that the four most "water-insecure" countries in the world were all in Africa.

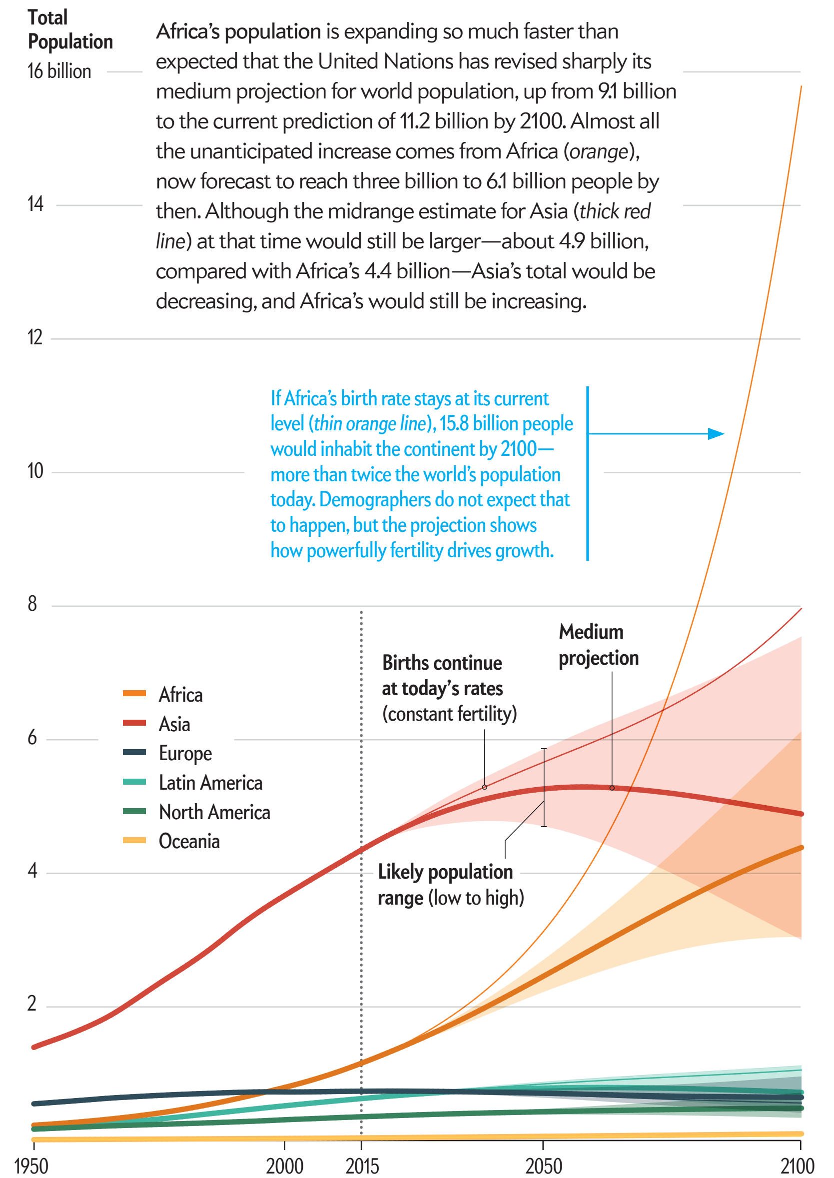
Competition for increasingly scarce resources is contributing to civil conflict and terrorism. In July 2014, on the Kenyan island of Lamu, 80 people died in a Muslim-Christian dispute over fertile soil. Some scholars attribute the rise of the brutal Islamist army Boko Haram in Nigeria at least in part to the clash of herders and farmers over the drying scrublands of the Sahel. The specter of few prospects for men in their teens and 20s to earn income also fuels aggression across central Africa. "If there were more jobs, in agriculture in particular, there would be less frustration and less conflict in Plateau State," says Becky Adda-Dontoh, an adviser to the Nigerian government, speaking of a jurisdiction in the eastern-central part of the country where Boko Haram is active.

The Washington, D.C.–based Fund for Peace ranks four African countries—Sudan, South Sudan, Somalia and the Central African Republic—as the world's most fragile, least able to govern their territory and maintain a minimal level of security. In 2015 alone, hundreds of Africans drowned trying to flee to Europe.

BIG PICTURE

Africa Drives Global Population Growth

Africa's population is expanding so much faster than expected that the United Nations has revised sharply its medium projection for world population, up from 9.1 billion to the current prediction of 11.2 billion by 2100. Almost all the unanticipated increase comes from Africa (*orange*), now forecast to reach three billion to 6.1 billion people by then. Although the midrange estimate for Asia (*thick red line*) at that time would still be larger—about 4.9 billion, compared with Africa's 4.4 billion—Asia's total would be decreasing, and Africa's would still be increasing.



SOURCE: *WORLD POPULATION PROSPECTS: THE 2015 REVISION.* POPULATION DIVISION, DEPARTMENT OF ECONOMIC AND SOCIAL AFFAIRS, UNITED NATIONS, 2015. DOWNLOADED NOVEMBER 19, 2015 *http://esa.un.org/unpd/wpp/Download/Standard/Population*

Graphic by Tiffany Farrant-Gonzalez

more than 1.3 billion, according to the U.N.'s projections. Demographers Jean-Pierre Guengant of the Research Institute for Development in France and John May of the Population Reference Bureau predict that the continent's biggest cities will explode in size by 2050: Lagos, Nigeria, from 11 million residents in 2010 to 40 million; Kinshasa, Democratic Republic of the Congo, from 8.4 million to 31 million. A scene in the 2005 film *The Constant Gardener* offers a view of this future, with sweeps above Kibera in Nairobi, Kenya—the continent's largest slum, with half a million to a million residents (no one really knows the number). Kibera's corrugated-metal roofs extend almost to the horizon in every direction. Based on current projections, hundreds of communities this size would probably form across Africa by midcentury.

The prospect of a crowded, confrontational and urban continent has begun to worry Africa's national leaders, most of whom have traditionally favored population growth. They are starting to speak up. In 2012 the then prime ministers of Ethiopia and Rwanda called for new efforts to expand the use of family planning to "reduce poverty and hunger, preserve natural resources and adapt to the consequences of climate change and environmental degradation." Kenyan-born Musimbi Kanyoro, president of the Global Fund for Women, has recently called for "rights-based, culturally appropriate ways to slow population growth while enhancing human dignity and thoughtful development."

It is not surprising that access to family planning is one of the steps receiving renewed attention. Today only 29 percent of married African women of childbearing age use modern contraception. On all other continents the rate is solidly more than 50 percent. Surveys also show that more than a third of African pregnancies are unintended; in sub-Saharan Africa 58 percent of women aged 15 to 49 who are sexually active but do not want to become pregnant are not using modern contraception.

Djenaba, a teenage girl whom I interviewed some years ago, testified to that tension in her remote village in Mali, a country where only one woman in 10 uses contraception. Just past her midteens, she was already the mother of two young children. When I first asked how many children she wanted to have, she responded, eyes downcast, "As many as I can." But after half an hour of conversation she faced me directly, her eyes misting, and told me she wished she could take contraceptive pills to get some rest from childbearing and soon stop altogether.

Any transition to prosperity requires a significant fertility decline. But that "can only be achieved if contraceptive coverage increases markedly from present low levels to rates of about 60 percent by 2050," noted Guengant and May in a 2013 paper. "This will prove difficult to achieve."

EARLY SUCCESSES

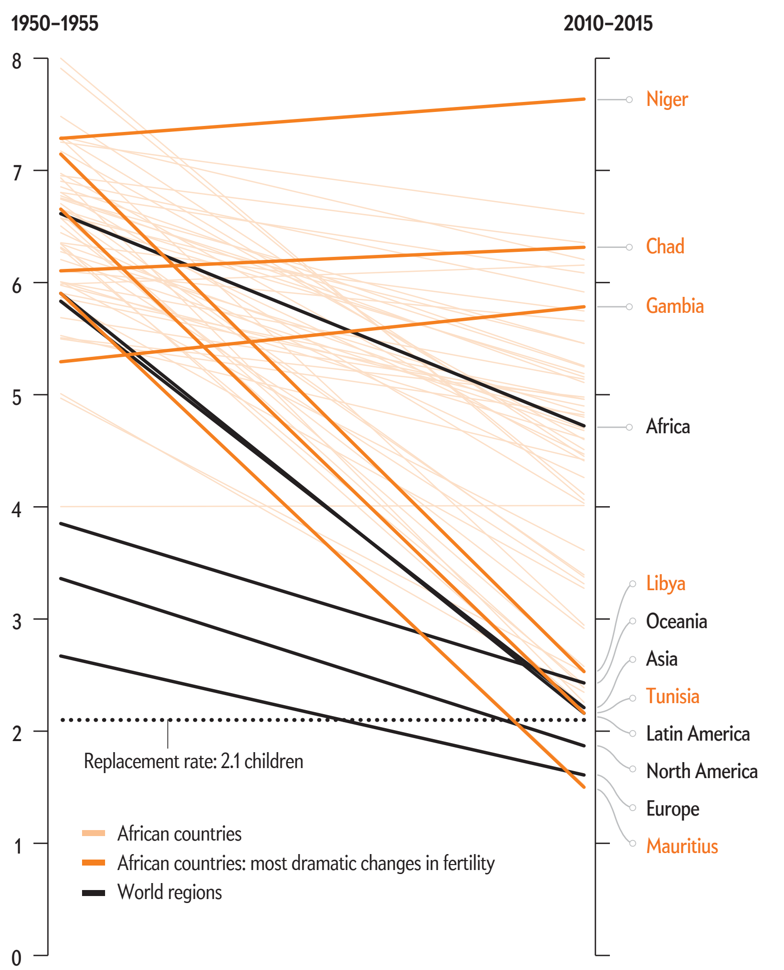
THE TREND TO URBANIZATION could, on its own, shrink family size somewhat. Children are more expensive to raise in cities

THE CHALLENGE

Fertility Rates Must Fall

The average number of children born to women in Africa has slowly decreased since the early 1950s, but the fertility rate has dropped faster in every other world region (*black lines*). The rate in Africa is still about 4.7 children; no other regions is above 2.5. The birth rate in certain African countries (*orange lines*) remains stubbornly high: 7.6 in Niger, 6.3 in Chad, 5.8 in the Gambia. These nations could learn from Mauritius, which has lowered its rate from six to 1.5, and Tunisia, which has dropped from 6.6 to 2.2. For population to level off in Africa or the world, average fertility has to settle at the replacement rate of approximately 2.1—the number at which offspring simply replace their parents.

Slow to Change (total fertility rate: children born per woman)



SOURCE: *WORLD POPULATION PROSPECTS: THE 2015 REVISION*. POPULATION DIVISION, DEPARTMENT OF ECONOMIC AND SOCIAL AFFAIRS, UNITED NATIONS, 2015. DOWNLOADED NOVEMBER 19, 2015 *http://esa.un.org/unpd/wpp/Download/Standard/Population*

Graphic by Tiffany Farrant-Gonzalez

COMMUNITY HEALTH WORKERS are often most successful in changing minds. A local worker in Shompole, Kenya, tells young Masai mothers how to use condoms (*above*). An adviser in Laniar, Senegal, explains how an intrauterine device works (*right*).

and are less likely to contribute to their parents' income, and parents are more likely to shift from traditional to modern ideas about ideal family size and the use of family planning. Of course, that is not a full solution. Ironically, certain African countries have significantly reduced fertility rates and have lessons to teach. The greatest is the benefit of combining family-planning access with efforts to give women more control over their lives and families.

In the Arabic north and in South Africa and neighboring nations, fertility rates have declined to three or less, approaching those in the rest of the world. In contrast, in the three vast subregions—East, Central and West Africa—fertility rates range from four to seven or higher.

The bright spots began their work years ago. Africa's half-dozen small island states have some of the continent's smallest families. One of the most rapid fertility declines in history occurred in Mauritius, east of Madagascar. The average fell from more than six in the 1960s to 2.3 two decades later. Today the rate is about 1.5, comparable to Europe and Japan. The steepest drop took place in the 1960s and early 1970s in the absence of any economic growth. Mauritians were relatively well educated, women as well as men. And by the early 1960s the national government overcame opposition from various groups, including Catholics and Muslims, to successfully promote family planning. Within two decades four out of five reproductive-age women were using contraception.

In 1957 Tunisia's first president, Habib Bourguiba, set in motion a sea change in the legal status and reproductive health of women hard to imagine in a mostly Muslim country. Bourguiba guaranteed women full citizenship rights, including the right to vote and to remove the veil. He pledged universal primary school attendance for girls as well as boys, banned polygamy, raised minimum marriage ages and granted women the right to divorce. He legalized contraception and then subsidized abortions for women with large families. By the mid-1960s mobile family-planning clinics were offering oral contraceptives throughout the country. Bourguiba was no democrat—his tightly controlled National Assembly elected him president for life in 1975—but his social reforms were left in place after he was deposed in 1987. Tunisian fertility fell from seven children to two in the early 2000s (it has since ticked up slightly). Somewhat less dramatic and more recent examples of presidential leadership have helped ease fertility in Kenya, Ghana and South Africa.

Mauritius and Tunisia demonstrate that the key to trimming family size is a consistent focus on improving women's lives, including economic opportunities and legal guarantees that are as equal as possible with those for males. Despite perceptions to the contrary, national economic growth alone does not push fertility down powerfully.

HOME VISITS, here supported by the William and Flora Hewlett Foundation, are vital to bringing family-planning information to remote villages such as Mbale, Uganda (*above*).

AN INTEGRATED STRATEGY

HOW CAN THE REST of Africa duplicate such success? The first step is to recognize that women and couples, not governments, hold the right to decide how many children to have. Women who are treated by their governments and the people around them as equal to men are more likely to conclude that *they* should decide whether and when to become pregnant, with the net result being smaller family size.

Education, especially in secondary school, turbocharges this empowerment. Education teaches girls and young women about nutrition, medicine and vaccination. But education also opens up a world of opportunity—economic, social, civic, political and artistic. Education spurs young people to seek contraceptives and to plan smaller families as they learn about the world, their bodies and the potential to steer their own destinies. African women with no education have, on average, 5.4 children, according to the International Institute for Applied Systems Analysis. Women who have completed primary school have, on average, 4.3 children. A big drop, to 2.7, correlates with completion of secondary school. For those who go on to college, fertility is 2.2.

Better education of young men is also vital. Young people of both genders who complete comprehensive sex education courses are more likely to delay having sex, which reduces early and unwanted pregnancy. The HIV/AIDS pandemic stoked the spread of sex education, at least in southern and eastern Africa. But its quality is uneven, and it is absent altogether in much of the continent.

The impact of sex education and higher educational attainment by women can be squandered if family planning goes unsupported by governments and society at large, however. Even women with graduate degrees cannot manufacture their own contraceptives in their homes.

African leaders appear to be gradually recognizing this dire situation. Uganda's president Yoweri Museveni long opposed family planning, but in July 2014 he hosted an all-Africa conference on the need to make it more widely available. Government-funded voucher programs in Kenya and Uganda and subsidized maternal and child health care in Zimbabwe encourage low-income individuals and couples to visit clinics. Many walk out with a method of contraception that will prevent unwanted pregnancies and space out wanted ones. In Malawi, cash transfers from an experimental program to schoolgirls and their parents or guardians have encouraged school attendance, contributing to higher educational attainment, later sexual activity and marriage, and has reduced teen pregnancy.

Ethiopia's government recently recruited 38,000 health extension workers, armed them with information and supplies, and dispatched them to rural areas, where 80 percent of the country's population lives. Pedaling U.S.-donated bicycles to remote villages, the health workers offer family-planning information and contraceptives to women and, when they are supportive, their husbands. Fertility declined over a recent three-year period from 4.8 to 4.1. Similarly impressive declines are turning up in communities in Kenya and Ghana and even in the megacity of Kinshasa.

In many places, however, the leadership shift is halfhearted. The continent's mostly male presidents still seem to think there is strength in numbers and that women should not be reaching for equality with men. "It would help if African presidents would visit family-planning clinics," May says. "That can really make a difference in attitudes. But instead they always like to go to the immunization clinics."

CHANGING MEN'S ATTITUDES

INDEED, MUCH DEPENDS ON the men in women's lives. Unfortunately, helping women plan their families stealthily—by using contraceptive injections, for example—is a leading strategy because many male partners believe childbearing decisions are theirs alone to make. Men also tend to want one to three more children than women do, not surprising given who gets pregnant, gives birth and handles most of the child care.

The differences in male and female outlooks sometimes get expressed in ugly ways. A woman's interest in or use of contraception can make her vulnerable to abuse from her male partner. A Nigerian study presented at a 2011 conference found that 30 percent of women who are or ever were married report some degree of "intimate partner violence"—sexual, physical or emotional. Contraceptive users and women with some primary education were more likely than nonusers and those with no schooling to have en-

SCIENTIFIC AMERICAN ONLINE For a video graphic showing 2,000 years of global population growth, see ScientificAmerican.com/feb2016/engelman countered such abuse. Even in Rwanda, with all its attention to female empowerment, 31 percent of women reported in 2010 that they had experienced violence from a husband or partner.

Actual violence was not the barrier for then 26-year-old Faridah Nalubega. She intended to have just two or three children, the most she felt she could afford by selling fried fish in Kampala, Uganda, according to PAI, a U.S.-based family-planning advocacy group. But she ended up with six children—in large part, she told PAI, because her husband forbade her to use contraceptive pills and her local family-planning clinic offered no suitable alternative.

Attitudes may be changing. Men whom I have interviewed in my travels in Africa have spoken wistfully of the days when there were fewer people and more forests, and sometimes they have voiced support for family planning as a way to slow these discouraging trends. Some of them have also expressed respect for women as colleagues. "The women on the council see things in different ways and come up with ideas none of the rest of us would have thought of," a male city council member told me in Tanzania. "We wouldn't want to lose them now." His statement reflects a larger truth: fertility can decline in part through what sociologists call "ideational change"—a rising acceptance of concepts that were once viewed as radical or even abhorrent. Tanzania, for example, is pondering a draft constitution that would grant women equal status to men in property ownership, inheritance and other legal rights.

Women are moving forcefully into unprecedented positions of government leadership, too. Today Rwanda has a minister of gender and a parliament with the highest proportion of women in the world—nearly two thirds. Joyce Banda was Malawi's president from 2012 to 2014. Liberia's current president is Ellen Johnson Sirleaf. Ngozi Okonjo-Iweala served as foreign minister and finance minister of Nigeria, the first woman to hold either post. The chair of the African Union Commission is Nkosazana Dlamini Zuma of South Africa. When girls see women in these positions, it alters their calculus about their own options.

PUSH WITHOUT PUSHING

NIGER IN WEST AFRICA offers an example of why an integrated strategy for lowering population growth, combined with government involvement, is so critical. There, in one of the world's poorest nations, the average fertility is 7.5 children per woman, and it has barely dipped since measurements began in 1950. Women and men surveyed say that the ideal family is even larger.

Demographers are a bit stumped as to why, but the high number probably stems from a combination of factors. They include religious beliefs, high death rates among young children, a large proportion of rural residents who depend on children to work poor land, large families being valued as a matter of status (especially for men), and women having low status (children prop up women's value in marriages, which are often polygamous). Childrearing is typically shared in extended families, notes demographer John Casterline of Ohio State University, easing the burden—and therefore easing the decision among parents to have another baby. Mamadou Tandja, president of Niger until 2010, used to spread his arms to denote the vast expanse of his country, bigger than Texas, telling visitors there was plenty of room for a much larger population.

A multipronged strategy requires strong engagement by government, community involvement and money, says Guengant, who has worked in West Africa and elsewhere on the continent. Often, however, he notes, governments fail to deliver on promises. At a 2012 international conference in London, a top Ghanaian Ministry of Health official assured the audience that his country's national health insurance program would reimburse personal expenses for family planning. Three years later the government is still pondering how to put the reimbursement plan into effect. Implementation by most governments "is a disaster," he says. "You have to have a push, either from government or from civil society, or both. In Africa, we miss the push."

"Push" is a touchy word among those who fear a population-control mentality. But outside of China, where the new two-child policy still limits reproductive freedom, no one is proposing limits on family size. Guengant is talking about pushing leaders to step up—to bravely raise public and policy conversations about slower population growth. What is needed is a Zen approach to the art of population—a way of easing growth not by striving directly for that outcome but by creating the conditions through which it occurs naturally.

Cultures and attitudes can evolve—often rapidly, as the drop in fertility rates in Tunisia and Mauritius demonstrate. Sadly, I have no idea what became of Djenaba in Mali and her hopes of managing her own childbearing. But her words are a reminder that efforts to assure all women the means and social support to prevent unwanted pregnancies, without coercion or pressure, are paramount. Such efforts mark the only ethical and feasible path to an African population that slows its growth and eventually stops growing, as all populations must. There, and everywhere, such a population can live prosperously, resiliently and in harmony with the environment.

The empowerment of women needs no demographic justification. But it happens that women who can raise their sights high and manage their own lives also decide—and manage—to have fewer children and to have them later in life. Even if population growth did not matter, the future of Africa and the world would be better if every African girl and woman were healthy and educated and free to reach for her own ambitious dreams, to safely refuse unwanted male attention, and to have a child only when and with whom she chooses.

Whether Africa finishes the century with several billion people or something much closer to its current 1.2 billion could make all the difference in its development, prosperity and resilience in the face of inevitable challenges. SA

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NEUROSCIENCE

THE POWER OF THE INFANT BRAIN

An understanding of formative periods of intense learning during childhood suggests strategies for correcting neurological and psychiatric disorders later in life

By Takao K. Hensch

Illustration by Harry Campbell

Takao K. Hensch is a joint professor of neurology at Harvard Medical School and Boston Children's Hospital and a professor of molecular and cellular biology at Harvard's Center for Brain Science.

WHAT'S ON YOUR MUSIC PLAYER? IF YOU'RE OLDER THAN 30 YEARS, it probably includes songs from your teenage years. Childhood and adolescence are the most impressionable period of a person's life. The earliest memories and experiences are essential in shaping character—and they profoundly influence everything that comes next. "The habits we form from childhood make no small difference, but rather they make all the difference," Aristotle proclaimed more than 2,000 years ago.

The latest findings from brain science are lending a new appreciation to the proverb. New discoveries made during the past 15 years spell out more clearly how the brain begins to wire itself in infancy and toddlerhood—and how to tinker with brain circuits to treat the most serious neurological and psychiatric illnesses.

The brain builds the right connections during intervals of intense development—some lasting months, others years—that are known as critical periods. Most occur in infancy, but some arrive as late as the teenage years. Neuroscientists have already identified critical periods for vision, hearing, language and various forms of social interaction. During a critical period, the child brain enters into an intimate pas de deux with the outside world. Incoming photons and sound waves serve as cues for the brain's molecular machinery to lay down and select the links among brain cells that will last into adulthood and old age.

If a critical period occurs too soon or too late or if it fails to begin or end when it should, the consequences can be dire. A child might be left partially blind or become susceptible to conditions such as autism. A baby with, say, a hereditary cataract in one eye that keeps her from seeing her surroundings will lose sight because the connections among brain cells will not have wired up properly during a critical period that begins in infancy and tapers off gradually before ending at age eight. Once it is over, the child has an extremely limited chance of developing normal vision through that eye.

The original discovery of these formative stages came more than 50 years ago. (Torsten N. Wiesel and the late David H. Hubel received a Nobel Prize for some of the work in 1981.) For many years afterward, the conventional wisdom held that critical periods were fleeting and that once they ended, there was no way of going back. Recently new molecular tools for studying critical periods have overturned many of the prevailing ideas. Experiments in animals—and even some human studies—have demonstrated that a critical period might be reopened to repair broken brains well afterward.

The implications point to a startling possibility. We may one day be able to tweak chemical switches that reinstate pivotal intervals and let the brain rewire itself to treat neurological and psychiatric disorders ranging from amblyopia (lazy eye) to psychosis. An understanding of what happens in the baby brain may inspire more than the design of new drug treatments. It may also give educators, psychologists and policy makers a fundamental understanding of the basic process of child development or the consequences of parental neglect that will allow them to tailor schooling to fit the capabilities of each child at a particular stage of brain growth.

TRIGGERS AND BRAKES

THE BRAIN CHANGES ALL THE TIME, not just in infancy. Neuroscientists call it plasticity. When you learn how to juggle or use a

IN BRIEF

The child brain develops vision and other abilities during "critical periods," when the brain is primed to undergo lasting change in response to sensory and social stimuli.

Critical periods open at defined times during the course of childhood and adolescence to allow the molding and shaping of neural connections—a property known as brain plasticity.

Growing understanding of the molecules that both start and stop critical periods has let scientists gain a measure of control over their timing, restoring plasticity even in adulthood.

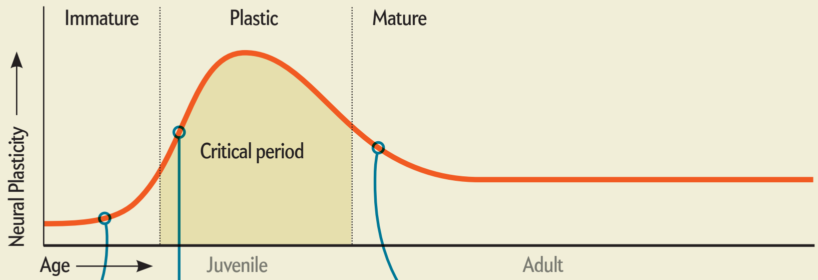
Regulating the biology of early development may one day allow drugs or medical procedures to restart critical periods later in life to correct early developmental problems.

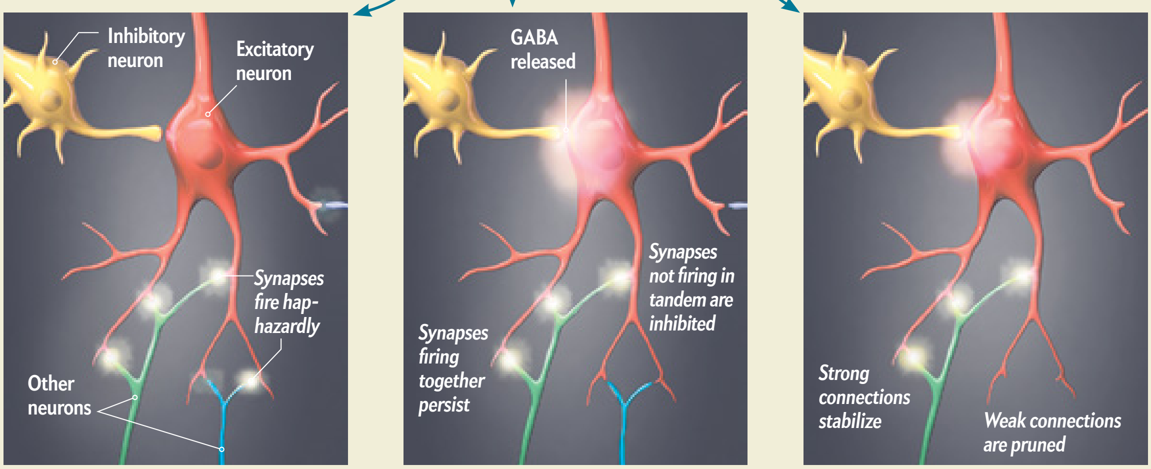
A Young Brain's Window on the World

A rite of passage in early life—the critical period—takes place when the brain uses sights, sounds and the rest of the sensory inflow from a child's surroundings to guide the neurodevelopmental process. During one such interval, the incoming visual imagery appears to calibrate the brain's cortex with the outside world. Visual stimuli determine which neuron wires to another to best respond to input from the eyes.

Bringing On Change

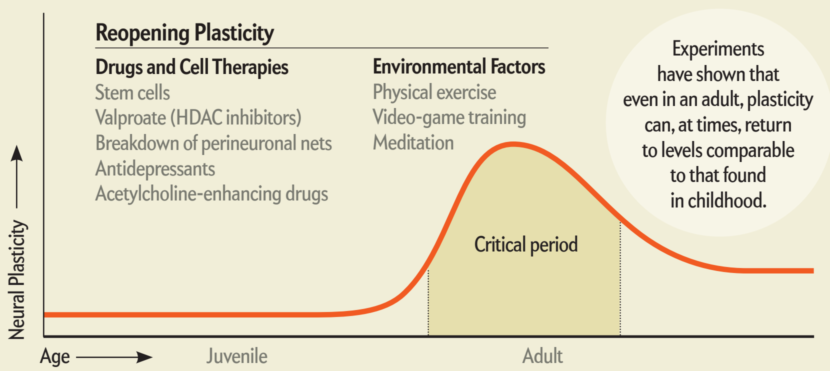
Neurons in the immature brain are highly active, firing in haphazard patterns. The neurotransmitter GABA orchestrates the brain plasticity of a critical period, in which only synapses that fire together survive, while those that do not are inhibited and eventually pruned. Once the critical period ends, the capacity to pare back synapses diminishes.





A Restart

Understanding of the molecular processes in the brain that bring about the plasticity of the critical period has enabled scientists to use drugs or behavioral measures, such as physical exercise, to demonstrate that the brain's connections can be molded at much later ages than once thought possible.



new phone app, subtle alterations occur at synapses, the sites where nerve signals travel between neurons. Mastering a new skill brings about biochemical changes in a neuron that results in either stronger or weaker transmission across synapses. This simple type of plasticity persists throughout a lifetime. A person can always learn new things.

During the critical periods of early childhood, however, especially momentous changes take place. A baby begins life with a thick overgrowth of synapses that must be pared back to do their job properly. The necessary structural changes—the culling of synapses—happen during the critical period.

Scientists who study critical periods often home in on the

Illustration by Mesa Schumacher (neurons), Graphic by Jen Christiansen visual system because it is relatively straightforward to manipulate. Shortly after birth, the visual cortex, located at the back of the head, begins to react to the flood of incoming light channeled from the eyes and the optic nerve.

What the eyes see stimulates cells in the visual cortex. Some of them then fire at the same time, resulting in new synapses forming between them—a process that gave rise to an oft-repeated adage: "Cells that fire together, wire together." Out-of-sync synapses that do not communicate in unison get clipped back. The critical period to connect the visual system of the infant brain ends after a few years, and the resulting wiring plan usually remains in place for a lifetime.

Scientists who study the neurobiology of child development want to learn how to gain a measure of control over the timing of critical periods to potentially correct missed opportunities or mistakes made in wiring up a developing nervous system. They have looked for a set of molecular switches—triggers and brakes—that mark the beginning and end of these intervals.

One key discovery has come from inspecting an important signaling molecule in the brain. The neurotransmitter GABA (short for gamma-aminobutyric acid) is best known for tamping down the firing of nerve cells. Our laboratory initially found that GABA—together with some companion molecules—plays a key role in determining when a critical period starts and stops. Indeed, we found one type of GABA-producing neuron, the parvalbumin-positive large basket cell, that very likely orchestrates the entire process.

On the face of it, a parvalbumin neuron would seem ill suited to take on this task of kicking off a critical period. GABA's typical role is to quiet neural activity. Why, then, should it trigger one of the most intense events in child development? What happens, it turns out, is that the neurotransmitter brings order to an otherwise chaotic scene.

During a baby's earliest months, the brain is always on. Neurons—aptly named excitatory cells—fire haphazardly, like people in a crowd all talking at once. It is only when the critical period begins that some semblance of structure is imposed. GABA emitted from parvalbumin cells tells the excitatory cells to quiet down and stop talking nonsense. They do so by extending long tendrils called axons that form connections. The axons wrap like a basket around nearby excitatory cell bodies, the central part of a neuron. Their reaching out tamps down excitatory cells' overheated activity, enabling the target cells to emit sharp and clear signals—attaining what we call an excitatory-inhibitory balance.

Our research looked carefully at this process in the visual system of rodents. We began by genetically tinkering with mice to lower their GABA levels. As a consequence, the critical period did not begin when expected. Later, when we administered a benzodiazepine drug, such as Valium, that increases GABA signaling, the critical period got back on track.

The experiment showed that we could, in principle, control precisely when critical periods begin or end and how long they last. This realization has far-reaching implications for treating neurodevelopmental disorders. Animal studies from a number of labs have now shown that either perturbed genes or environmental stress can upset the fragile balance between excitation and inhibition and start a critical period at the wrong time. Researchers have begun to focus on whether correcting the timing of critical periods might one day prevent or treat autism, schizophrenia or other neurological disorders by restoring the desired equilibrium.

BACK TO THE FUTURE

IT WILL TAKE YEARS, perhaps decades, of research before some of the most ambitious techniques tested in lab animals reach patients. Understanding critical periods, though, has also led to some compelling ideas for using drugs already on the market to restore a modest amount of plasticity in the adult brain.

A long-term goal would turn back the biological clock and restart a critical period. A lab at the University of California, San Francisco, tried to do this in rodents by transplanting embryonic cells that give rise to GABA-producing neurons in older brains after birth. After the transplant, another critical period began but only when these cells reached one month of age, indicating that timing was under the control of specific genes. When our lab deleted such timing genes in young animals, the start of even the normal critical period was delayed.

Another equally challenging approach to restoring plasticity would be to remove the brakes that prevent a critical period from restarting. One check on plasticity resides in a latticework of cartilagelike molecules called a perineuronal net. It wraps around the parvalbumin neurons as they mature, bringing to an end the critical period and thus preventing synapses from undergoing further structural changes.

The perineuronal net consists primarily of chondroitin sulfate proteoglycans, a molecular complex of proteins studded with sugars. Brakes on plasticity disappear when enzymes eat away at these molecules. A British-Italian team rescued aged rats with amblyopia after injecting such an enzyme, a chondroitinase, into their brain, which then dissolved the perineuronal net. At that point, a new critical period opened. The rats received the needed visual stimuli they had missed as pups, which enabled them to recover good vision.

Researchers at the Friedrich Miescher Institute for Biomedical Research in Basel adopted a similar approach. They first trained rats so that they responded fearfully to a particular stimulus—cowering, for instance, when a bell rang. Memories of frightening experiences are stored in cells of a brain area called the amygdala. Elimination of the perineuronal net around these cells initiated a critical period. The animals then successfully underwent a new training regimen that conditioned them to no longer be afraid when exposed to the stimulus, just like an infant rat.

The safety of a procedure that requires injection of an enzyme deep into the brain would come under intense scrutiny by the U.S. Food and Drug Administration—and so will not likely receive approval anytime soon. A number of existing drugs, however, may be able to enhance brain plasticity to some degree. Our lab has been involved in a collaboration to conduct a small pilot study that has shown that a generic drug for epilepsy and bipolar disorder enables an adult to learn new things almost as easily as a child does.

In the study, we used a drug that lifted another brake on brain rewiring. The drug—an HDAC inhibitor—works by turning off an enzyme that tightly coils up DNA, preventing the making of proteins that promote brain plasticity. We wanted to see if inducing plasticity would let a group of adults acquire perfect pitch—a skill that usually needs to be learned before the age of six through exposure to music. Healthy men in their 20s who

TETRIS THERAPY with a special version of the video game taps into brain plasticity to enable both eyes to work in tandem, improving vision in a subject with amblyopia, an impairment in which one eye exhibits stronger visual acuity than the other.

COURTESY OF MCGILL UNIVERSITY

received the drug were trained to distinguish tones in three octaves. None of them suddenly developed perfect pitch just by taking the drug, but by the end of the two-week training, they did perform significantly better at identifying these tones than did a placebo group of comparable size.

Commonly available drugs that increase the presence of other neurotransmitters—acetylcholine, serotonin and other molecules that indirectly control the rate of firing of neural circuits—may also help restore plasticity. Acetylcholine causes neurons to emit a sharply defined signal in moments of arousal. It does so by adjusting the balance between excitation and inhibition in much the same way that a critical period does.

Boston Children's Hospital is undertaking a clinical trial to determine whether a drug to treat Alzheimer's disease, called donepezil, which increases availability of acetylcholine, may restore normal vision to young adults with amblyopia by overcoming a brake on plasticity. Added acetylcholine means more of it can bind to its receptors on neurons. That limits the ability of a plasticity-inhibiting molecule—Lynx1—to dampen the activity of those receptors. Our previous studies have shown that removing this chemical relative of a snake toxin rekindles plasticity.

Acetylcholine is not the only neurotransmitter that may help treat amblyopia. Administering antidepressants such as Prozac that increase the levels of serotonin has alleviated amblyopia in rat experiments. In some cases, drugs may not even be needed. Action video games or meditation may also promote a heightened state of plasticity—and are being explored as possible treatments for amblyopia, attention-deficit/hyperactivity disorder and other conditions.

Researchers who work on critical periods often find themselves asking why these limits on learning exist in the first place. The ability to learn, say, Chinese as an adult as easily as a child does would provide an obvious benefit to all members of our highly social species. Why, then, have the brains of humans and many other animals evolved to limit their own malleability? Is there some inherent danger to reopening a critical period when we want to learn a new skill? After all, is not genius "nothing more nor less than *childhood recovered* at will," as French poet Charles Baudelaire once wrote?

Restricting plasticity may have ultimately evolved to protect brain cells. The high metabolic demands of parvalbumin cells generate free radical molecules that can damage brain tissue—one reason the perineuronal net may have evolved. A postmortem examination of the brains of patients with schizophrenia and other mental illnesses shows an overall loss of perineuronal nets and related neural brakes on plasticity.

Alzheimer's may provide a clue to the perils of unbridled plasticity. Higher-order brain areas, such as the associational cortex, responsible for complex cognitive functions, have evolved to remain plastic throughout a lifetime. These regions are less endowed with chondroitin sulfate proteoglycans that shut down critical periods, and they are also the first to experience the deaths of cells in this neurodegenerative disease.

Philosophical arguments also emphasize the inadvisability of letting the brain change too much. Opening and closing critical periods as desired may benefit treatment of neurological diseases. But an individual's basic identity is also shaped during these formative times. As humans develop ever more ingenious technological means to alter their environment, they will be tempted to find new ways to enhance plasticity in adulthood to adapt to the rapid-fire changes around them. If rekindling plasticity is not undertaken with the utmost care, the rewiring of the brain could threaten to undermine one's sense of self. Such vexing trade-offs should not be forgotten as we are lured into creating technologies that allow us to recapture the plasticity of childhood as adults to better adapt to the demands of a protean modern world. SA

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ASTRONOMY

MY LIFE AS A COMET HUNTER

The need to pass a French test, of all things, spurred half a century of cosmic sleuthing

By David H. Levy

I DECIDED TO BECOME A COMET HUNTER ON a bright, clear morning 50 years ago in Montreal. It was a bit of an impromptu decision. I had a French test coming up and knew that the examiner, a Mr. Hutchison, would ask me about my career plans. I had to come up with something that was both credible and easily translated into French.

About six years earlier I truly had become passionate about the night sky, but to stand up and say, "*Astronomie!*" was not enough. Mr. Hutchison would want details. I recalled a comet that had recently been discovered from Japan—one that eventually became the brightest of the 20th century. Without a further thought, I decided that I was going to be a searcher for comets, among other things. Not coincidentally, the English and French words for a comet (*une comète*) sound very much alike, and thus my new vocation was relatively easy to talk about in French.

By the time I arrived in school that day, I had developed a search plan that would last a lifetime. And true to the answer I gave Mr. Hutchison, I began on Friday evening, December 17, 1965, when the moon was a waning crescent and its light would not interfere too much. I have not stopped searching for comets since that night. Fortunately, working as a science journalist and giving lectures about the night sky—not to mention the loving support of my wife, Wendee—have allowed me to pursue my cosmic passion and still pay the bills.

Searching for comets was far easier than finding them. I had the right equipment—an eight-inch-diameter telescope named Pegasus, later augmented by more powerful instruments. But actually discovering my first comet took almost 19 years. On that particular night, November 13, 1984, I got my bearings by finding a faint galaxy, then a planetary nebula (the remnant of an ancient star's lethal outburst) and then a pretty cluster of stars. My attention was soon drawn to a fuzzy object a bit to the cluster's south. Although its glow was diffuse, it lacked the symmetry of a galaxy. Nor did it have the mottled appearance of a densely packed star cluster. I drew the object and some surrounding stars as reference points on a sketch pad. As I looked through the telescope again and again and made new drawings, I slowly realized that this fuzzy object was not staying in the same place relative to the nearby stars but was creeping northward, as only a comet would.

I telephoned an astronomer at Lowell Observatory in Flagstaff, Ariz., who confirmed my find with an abrupt, "Better send a telegram." I felt as though I could float right up to the sky I loved so much. It turned out that Michael Rudenko discovered the comet independently the next evening, and thus the new object became known as Comet Levy-Rudenko.

In the following years, I discovered 22 other new comets, either working alone or with others. Perhaps the most famous was Comet Shoemaker-Levy 9, which was the first comet ever observed crashing into a planet, Jupiter. Working together in 1993, Carolyn and Eugene Shoemaker and I found this odd space ball, 16 months before its fiery collision.

I am still searching for comets, but I rather doubt I will find any more new ones. Comet hunting has become completely automated—with computers scanning robotically captured photographs of the night sky for fuzzy objects that move in just the right way. My original method—peering directly into a telescope to witness what no one else had seen before—is no longer needed. I still enjoy the visual hunt, however. After 50 years, it is the joy of the search, more than the discoveries, that keeps me going. SA

MORE TO EXPLORE

Panoramic Survey Telescope & Rapid Response System (Pan-STARRS): http://pan-starrs.ifa.hawaii.edu/public

Rosetta Mission to Comet 67P/Churyumov-Gerasimenko: www.esa.int/Our_Activities/Space_Science/Rosetta and http://rosetta.jpl.nasa.gov

FROM OUR ARCHIVES

Comet Shoemaker-Levy 9 Meets Jupiter. David H. Levy, Eugene M. Shoemaker and Carolyn S. Shoemaker; August 1995.

scientificamerican.com/magazine/sa

Photograph by Jamey Stillings

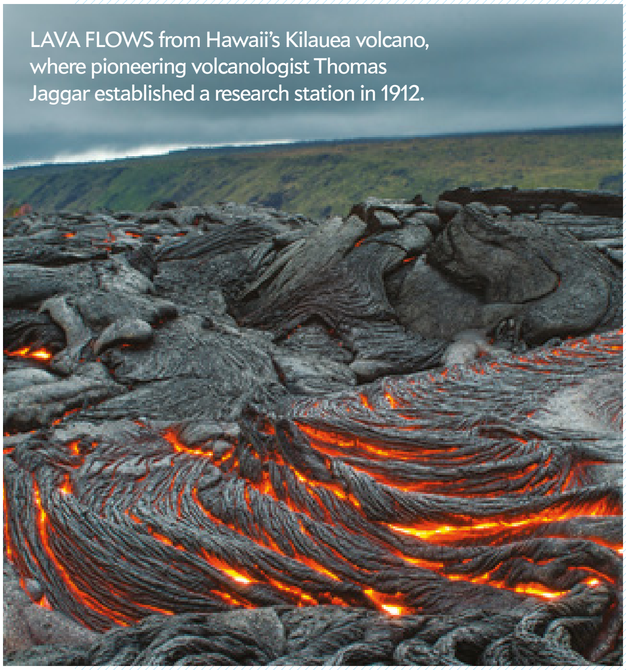
STARGAZER
David H. Levy, who has discovered 23 comets, poses at Jarnac Observatory in Vail, Ariz., with one of his favorite telescopes, Minerva, a six-inch reflector.

SCIENTIFIC AMERICAN ONLINE Learn more about Comet Shoemaker-Levy 9 at ScientificAmerican.com/feb2016/sl9

RECOMMENDED

By Clara Moskowitz

MORE TO EXPLORE
FOR MORE BOOK RECOMMENDATIONS, VISIT
SCIENTIFICAMERICAN.COM/FEB2016/RECOMMENDED

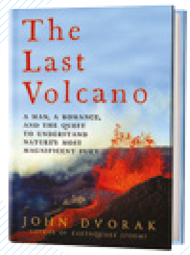


LAVA FLOWS from Hawaii's Kilauea volcano, where pioneering volcanologist Thomas Jaggar established a research station in 1912.

GRANT KAYE *Aurora Photos*

The Last Volcano: A Man, A Romance, and the Quest to Understand Nature's Most Magnificent Fury

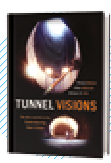
by John Dvorak. Pegasus Books, 2015 ($28.95)



In the spring of 1902 a young geologist named Thomas Jaggar arrived in Martinique to observe a scene of desolation—piles of rubble, heaps of volcanic ash and charred bodies everywhere—in the wake of an eruption from Mount Pelée. The trip changed the course of Jaggar's life, spurring him to dedicate his career to the study of volcanoes and how to protect people from them. Volcano expert Dvorak chronicles Jaggar's quest, following him from his comfortable position at Harvard University to the relative wilds of the island of Hawaii, where he founded a small station on the rim of the Kilauea volcano to monitor an active lava lake. There he met a widowed schoolteacher who became his wife and eventually his partner in volcanology. The two shared a reverence for volcanoes as well as a horror at the destruction they cause, and their story is an inspiring tale of devotion, both to science and to each other.

Tunnel Visions: The Rise and Fall of the Superconducting Super Collider

by Michael Riordan, Lillian Hoddeson and Adrienne W. Kolb. University of Chicago Press, 2015 ($40)



Most good science stories are tales of discovery and success, but failure can be just as riveting. Here two historians and an archivist describe the greatest particle physics experiment that never was. The Superconducting Super Collider (SSC), a planned 87-kilometer ring in Texas, would have crashed protons together at higher energies than any accelerator before or since, dwarfing even the current Large Hadron Collider at CERN, where the Higgs boson was discovered. But in 1993 Congress pulled the plug on the more than $10-billion project because of cost overruns, mismanagement and changing political tides. The authors examine what went wrong and what lessons the failure of the SSC can impart in an era when such Big Science projects are increasingly central to scientific research.

Contact Sport: A Story of Champions, Airwaves, and a One-Day Race around the World

by J. K. George. Greenleaf Book Group Press, 2016 ($22.95)

Huddled in nylon tents crammed with radio equipment, screens and knobs, 59 two-person teams spread across the wilderness of eastern Massachusetts raced to make radio contact with as many people as they could in 24 hours. These were the contenders of the 2014 World Radiosport Team Championship, the pinnacle event of the surprisingly thrilling world of competitive ham radio. Held every four years in various locations around the world, the contest challenges teams to scan the airwaves for other ham operators to connect with, either by voice or by Morse code, awarding points for each contact and extra for those in far-off locales. Writer and radio enthusiast George offers an insider's account of the frantic messages, last-minute antenna malfunctions and aggressive jockeying for coveted wave bands that defined the spirited contest.

Home: How Habitat Made Us Human

by John S. Allen. Basic Books, 2016 ($28.99)

"Home is not simply a location on the landscape where a person lives; it has a privileged place in our cognition," neuroanthropologist Allen writes. Whether you live in a tepee or a town house, "home" should ideally mean a sense of safety, comfort and well-being. It satisfies our need for shelter from the elements, a place to rest and recover, protection from predators and access to mates. The concept of home, Allen explains, divides the world in two: a domestic domain and everything else, simplifying the otherwise intimidating expanse around us. He investigates the neuroscience and psychology of "feeling at home" and how that feeling has granted an adaptive advantage to the human species, enabling the advances in culture and technology that separate us from our primate cousins. At a time when many people around the world lack a place to call their own, Allen shows why we all deserve one.

Michael Shermer is publisher of *Skeptic* magazine (www.skeptic.com). His new book is *The Moral Arc* (Henry Holt, 2015). Follow him on Twitter @michaelshermer

Afterlife for Atheists

Can a brain's connectome be preserved forever?

By Michael Shermer

The soul is the pattern of information that represents you—your thoughts, memories and personality—your self. There is no scientific evidence that something like soul stuff exists beyond the brain's own hardwiring, so I was curious to visit the laboratories of 21st Century Medicine in Fontana, Calif., to see for myself an attempt to preserve a brain's connectome—the comprehensive diagram of all neural synaptic connections.

This medical research company specializes in the cryopreservation of human organs and tissues using cryoprotectants (antifreeze). In 2009, for example, the facility's chief research scientist Gregory M. Fahy published a paper in the peer-reviewed journal *Organogenesis,* documenting how his team successfully transplanted a rewarmed rabbit kidney after it had been cryoprotected and frozen to –135 degrees Celsius through the process of vitrification, "in which the liquids in a living system are converted into the glassy state at low temperatures."

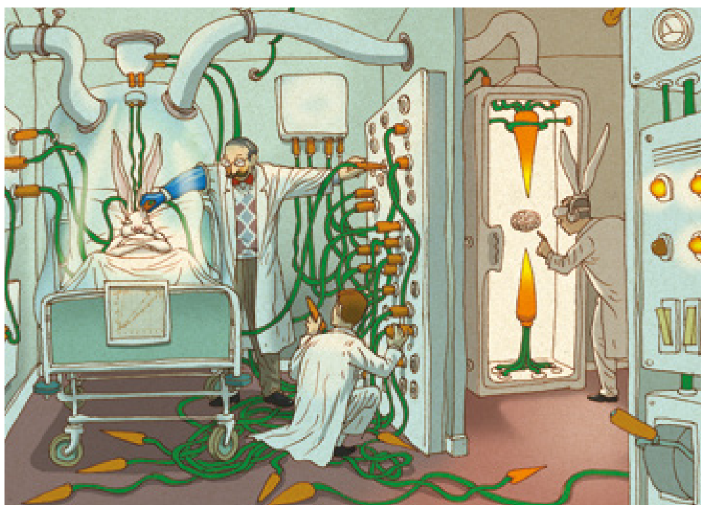
Can brains be so preserved? Fahy and his colleague Robert L. McIntyre are now developing techniques that they hope will win the Brain Preservation Technology Prize, the brainchild of neuroscientist Kenneth Hayworth (I'm on their advisory board as the *advocatus diaboli*). As I write this, the prize is currently valued at more than $106,000; the first 25 percent of the award will be for the complete preservation of the synaptic structure of a whole mouse brain, and the other 75 percent will go to the first team "to successfully preserve a whole large animal brain in a manner that could also be adopted for humans in a hospital or hospice setting immediately upon clinical death."

I witnessed the infusion of a rabbit brain through its carotid arteries with a fixative agent called glutaraldehyde, which binds proteins together into a solid gel. The brain was then removed and saturated in ethylene glycol, a cryoprotective agent eliminating ice formation and allowing safe storage at –130 degrees C as a glasslike, inert solid. At that temperature, chemical reactions are so attenuated that it could be stored for millennia. If successful, would it be proof of concept?

Think of a book in epoxy resin hardened into a solid block of plastic, McIntyre told me. "You're never going to open the book again, but if you can prove that the epoxy doesn't dissolve the ink the book is written with, you can demonstrate that all the words in the book must still be there … and you might be able to carefully slice it apart, scan in all the pages, and print/bind a new book with the same words." Hayworth tells me that the rabbit brain circuitry he examined through a 3-D scanning electron microscope "looks well preserved, undamaged, and it is easy to trace the synaptic connections between the neurons."

This sounds promising, but I have my doubts. Is a connectome precisely analogous to a program that can be uploaded in machine-readable format into a computer? Would a connectome so preserved and uploaded into a computer be the same as awakening after sleep or unconsciousness? Plus, there are around 86 billion neurons in a human brain with often 1,000 or more synaptic connections for each one, for a total of 100 trillion connections to be accurately preserved and replicated. Staggering complexity. And this doesn't include the rest of the nervous system outside the brain, which is also part of your self that you might want resurrected.

Hayworth admitted to me that a "future of uploaded posthumans is probably centuries away." Nevertheless, he adds, "as an atheist and unabashed materialist neuroscientist, I am virtually certain that mind uploading is possible." Why? Because "our best neuroscience models say that all these perceptual and sensorimotor memories are stored as static changes in the synapses between neurons," which is what connectomics is designed to record and preserve, allowing us to "'hit pause' for a few centuries if we need to." Imagine a world in which "the fear of death, disease and aging would have been mostly removed," he says.



It sounds utopian, but there's something deeply moving in this meliorism. "I refuse to accept that the human race will stop technological and scientific progress," Hayworth told me. "We are destined to eventually replace our biological bodies and minds with optimally designed synthetic ones. And the result will be a far healthier, smarter and happier race of posthumans poised to explore and colonize the universe."

Per audacia ad astra. SA

SCIENTIFIC AMERICAN ONLINE
COMMENT ON THIS ARTICLE AT
SCIENTIFICAMERICAN.COM/FEB2016

Illustration by Izhar Cohen

Steve Mirsky has been writing the Anti Gravity column since a typical tectonic plate was about 35 inches from its current location. He also hosts the *Scientific American* podcast Science Talk.

Spinning Our Wheels

Some words may not mean what you think they mean

By Steve Mirsky

The sign reads "Share the Road." It's usually a bright yellow diamond featuring a black line drawing of a bicycle. Variations on the sign exist, but they all pretty much send the message that cars should be on the lookout for cyclists and give them some breathing room.

Or at least that's what I, a cyclist sometimes and a motor vehicle operator other times, assumed was the message they sent. Especially given that the occupants of even a small automobile will barely feel a car-bicycle crash that will at the very least likely bust a bike rider's ribs and crack a collarbone.

A recent, study, however, rocked my two-wheeling world: "Although often described as a reminder to motorists that bicyclists may use the travel lane, bicyclists frequently complain that motorists interpret the sign to mean that they should get out of the way," wrote North Carolina State University researchers George Hess and M. Nils Peterson in the journal *PLOS ONE*. They noted that the state of Delaware, which is just wide enough for two lanes of traffic in each direction, got rid of its "Share" in November 2013 because, according to a state document, "some believe the plaque puts more onus on the bicyclist to share the road than the motorist."

Hess and Peterson conducted a Web-based survey of attitudes about the rights of cyclists to some breathing room on the road. They found that signs reading "Share the Road" had virtually the same effect on respondents' mentality as did no signage at all. But an alternative wording that appeared to at least somewhat alert people to the life and limb of bike riders did exist. "Bicycles May Use Full Lane" got more people to say that a driver should wait until it's safe to pass and then give the bike a wide berth.

Whether such signage will translate into behavioral changes among real drivers remains to be seen. And based on my experience cycling while decked out in high-vis neon-yellow clothing and lit up like the Rockefeller Center Christmas tree, a lot of drivers do not see all that well.

An even bigger public health issue exists that involves the interpretation of language. The term "antibiotics" has often mystified members of the lay public who do not know the difference between bacteria, which antibiotics can fight, and viruses, against which antibiotics head for the egress. (See Barnum, P. T., on sowing sign uncertainty.) Now we learn via research by Wellcome Trust, a global health foundation charity based in London, that the expression "antibiotic resistance" creates further confusion.

If you've heard of MRSA but think it's Mr. A's wife, antibiotic resistance is a growing and deadly problem referring to populations of bacteria evolving so that they are no longer killed by a given drug—the bacteria have become resistant to the antibiotic. But in interviews conducted for Wellcome Trust in London, Manchester and Birmingham, researchers encountered an unwelcome frustration, as it noted in a press release: "Researchers found that most people, if they had heard of antibiotic resistance at all, thought that it was their body which becomes resistant to antibiotics, rather than the bacteria that cause drug-resistant infections. This misconception often makes people feel like antibiotic resistance is someone else's problem." Which it is, until it isn't, regardless of the correct usage of the terms.

"The misconception could help to explain why many people who are prescribed antibiotics fail to complete the course, believing that this will prevent their bodies from becoming resistant," the press release continued. This strategery (see Ferrell, Will, on misunderestimation) helps to keep the patient infected and exacerbates the real problem. It's an "Appointment in Samarra" situation, with the added wrinkle of not making sense.

Wellcome Trust thus recommends that "doctors, the media and other communicators talk about 'drug-resistant infections' or 'antibiotic-resistant germs', rather than 'antibiotic resistance'. This makes it easier to understand that it is bacteria that acquire resistance, not people's bodies." So whether on a bike ride or on antibiotics, don't stop until you finish the course. SA

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SCIENTIFICAMERICAN.COM/FEB2016

Illustration by Matt Collins

The Agenda Setters

Bringing Science to Life

Photos by Getty Images for the Breakthrough Prize and Justin Bishop

Breakthrough Prize Ceremony

NASA Ames Research Center | Mountain View, CA | November 8, 2015

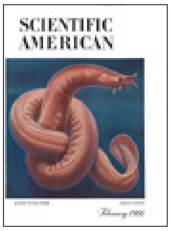
SCIENTIFIC AMERICAN was once again a partner with **The Breakthrough Prize**, which celebrates the best scientific work and inspires the next generation of scientists. Founded by Yuri and Julia Milner, Mark Zuckerberg and Priscilla Chan, Sergey Brin and Anne Wojcicki, and Jack Ma and Cathy Zhang, this year's Breakthrough Prize awarded the world's top scientists in the fields of Life Sciences, Fundamental Physics and Mathematics $3M each for a total of $21.9M in prizes.

Host Seth MacFarlane and award presenters Russell Crowe, Hilary Swank, Kate Hudson, Christina Aguilera and Pharrell Williams joined leaders from Silicon Valley and paid tribute to the world's most brilliant minds: those taking the biggest leaps towards curing diseases, building new technologies and bringing us closer to understanding the nature of the cosmos.

50, 100 & 150 YEARS AGO

INNOVATION AND DISCOVERY AS CHRONICLED IN *SCIENTIFIC AMERICAN*

Compiled by Daniel C. Schlenoff

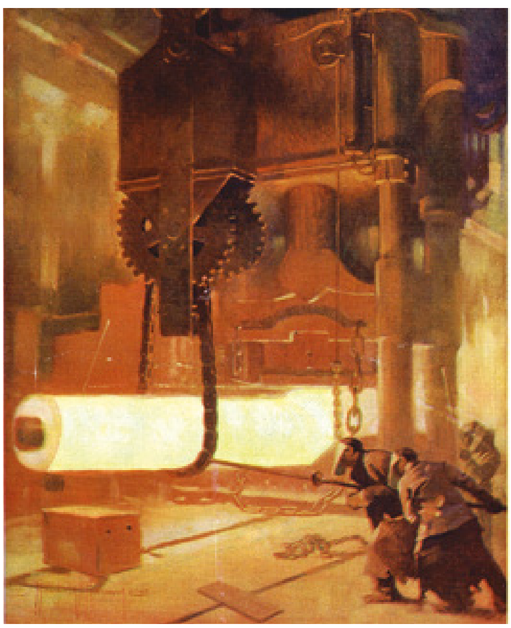


February 1966

Neutrinos Detected

"Two miles underground in a gold mine near Johannesburg, South Africa, an experiment is under way to study high-energy neutrinos produced by cosmic-ray collisions in the earth's atmosphere. On October 27, 1964—13 months after the selection of the South African site—our equipment registered the first deep-underground observation of a sister, or cosmic-ray, muon. Then on February 23, 1965, the detectors recorded a muon that had traveled in a horizontal direction—the first 'natural' high-energy neutrino had been observed! Since last February we have observed in our equipment some 80 sister muons and 10 daughter muons. These statistics are beginning to yield the first experimental estimate of the interaction probability for high-energy neutrinos.—Frederick Reines and J.P.F. Sellschop"

Reines shared the 1995 Nobel Prize in Physics for his work on neutrino detection.

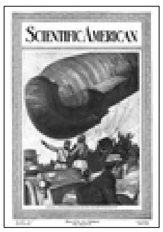


SCIENTIFIC AMERICAN, VOL. CXIV, NO. 6; FEBRUARY 5, 1916

1916: Workers manipulate a large-caliber naval gun in a giant forge during its manufacture. Desperately needed at the time, such armaments required extensive industrial capacity.

Jet Lag

"A series of tests carried out by the Federal Aviation Agency has substantiated the common complaint of air travelers that swift transition through several time zones disturbs their bodily and even their mental functions. Sheldon Freud, an Air Force psychologist who has worked on the testing, said that the reaction of the passengers made it important to test the crews. 'These men are responsible for the lives of millions of passengers every year,' he said. Freud also raised a question about supersonic flights, which will be at least twice as fast as today's jet flights: 'Will we have to rest twice as long afterward? Is it worth while getting over there in such a hurry?'"



February 1916

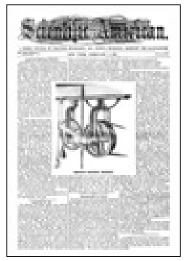
Naval Arms Race

"The 'California,' 'Mississippi' and 'Idaho' are to be armed with a new type of 14-inch gun, which will show a considerable increase of power over the 45-calibre gun. The new piece is six feet longer in the bore than the 45-calibre 14-inch gun. Rear-Admiral [Joseph] Strauss, Chief of Ordnance, states that these new guns are capable of penetrating the heaviest side armor at oblique impact at the greatest effective battle range. It is gratifying to learn that the new type of 16-inch, 45-calibre gun, built at the Washington Gun Factory, has fulfilled the highest expectations [*see illustration*]."

For a look at wartime industry in 1916, see a selection of images at www.ScientificAmerican.com/feb2016/industry

Blessed Communication

"According to a report from the Rome correspondent of a prominent news service, Vatican circles announce that the Pope [Benedict XV] is preparing to bless wireless telegraphy officially, thus restoring the ancient custom of the Church to bless inventions which confer great benefits on humanity."



February 1866

City Sewers

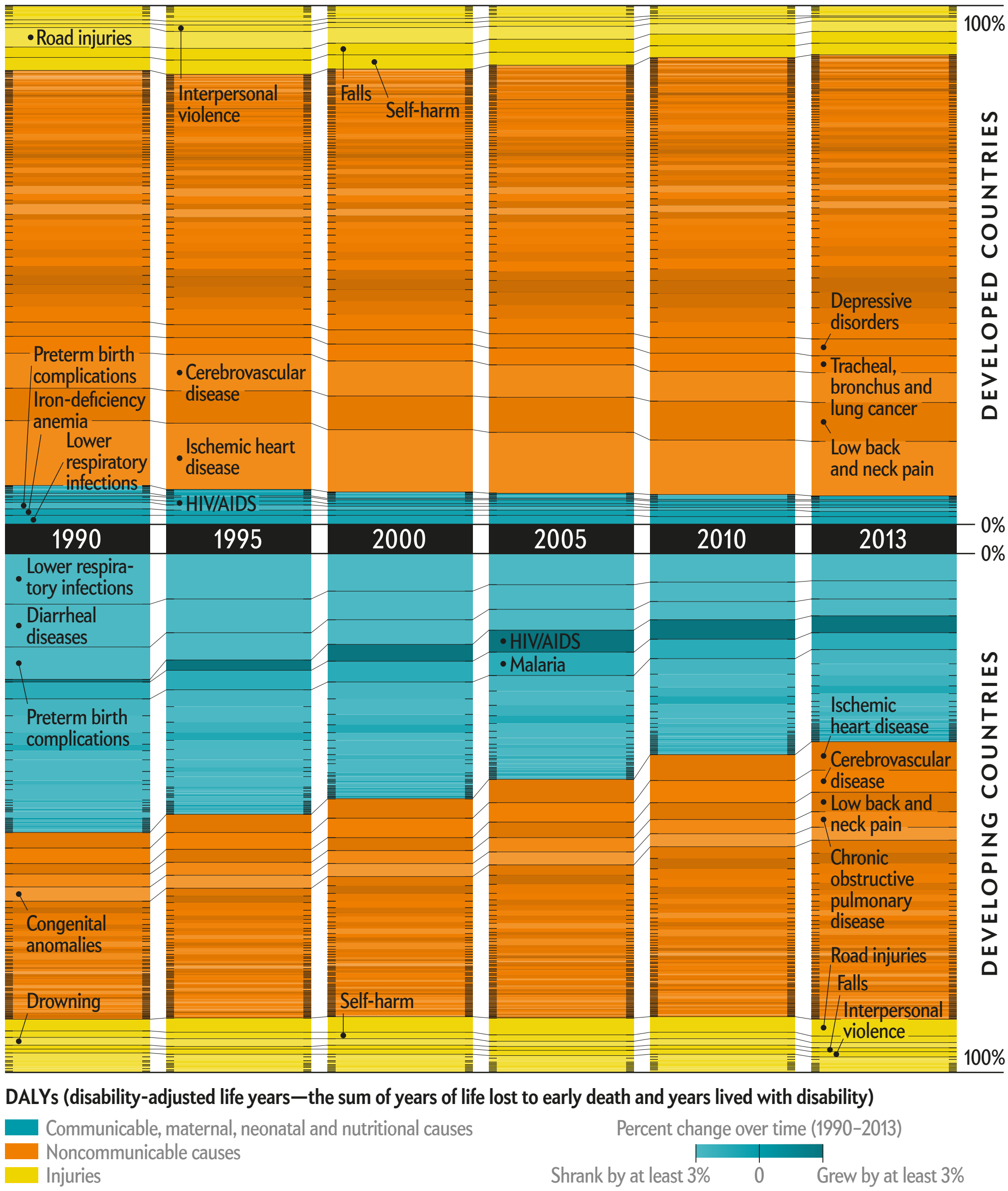
"The Thames bridges sink into comparative insignificance when compared with the great metropolitan drainage works executed during the last few years. There are 82 miles of main sewers in London. The total pumping force employed is 2,380 nominal horsepower; and if the engines were at full work night and day, 44,000 tons of coal per annum would be used. The sewage to be intercepted by the works on the north side of the river at present amounts to 10,000,000 cubic feet, and on the south side to 4,000,000 cubic feet per day; but provision is made for an anticipated increase in those quantities. In excavating for the works, a large number of animal remains, ancient coins, and other curious objects were found, most of which have been deposited in the British Museum."

Metric System Superiority

"The last monthly report of the Agricultural Department has an exceedingly able article on the French system of weights and measures. We have no doubt if every Member of Congress would devote the very little effort that is required to master the system, it would be immediately adopted by an almost unanimous vote. A child will master the whole system in very little more time than is required to commit to memory the table of avoirdupois weights. Let Congress pass an act declaring that, after the first of January, 1867, the French system of weights and measures [metric] shall be the legal system of the country. Before the expiration of a year, there will be a general expression of wonder that we endured the enormous labor and inconvenience of our old complicated and incongruous system so long as we did."

SCIENTIFIC AMERICAN ONLINE
FOR A GRAPHIC ON RISKY BEHAVIORS THAT CAN SHORTEN LIFE SPAN, SEE SCIENTIFICAMERICAN.COM/FEB2016/GRAPHIC-SCIENCE

Causes of Premature Death and Disability, 1990–2013

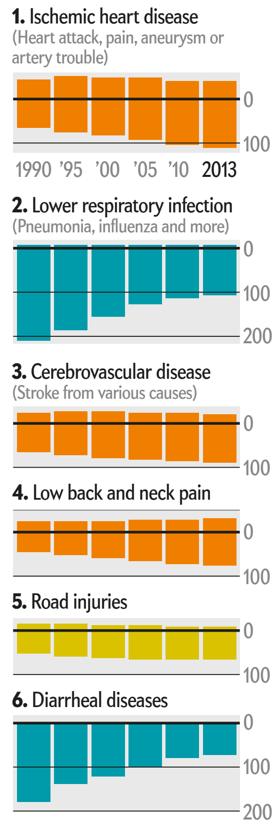


Top Threats

Heart disease is the world's leading health menace. Yet the proportion of premature deaths and disability it causes (*below*) is actually going down in developed countries, offset by a rise in developing nations. The same trend is occurring with cerebrovascular disease. In contrast, the prevalence of low back and neck pain is increasing everywhere.

2013 Rank, Total DALYs (millions)

Developed countries (*top*) and developing countries (*bottom*)



Disease Squeeze

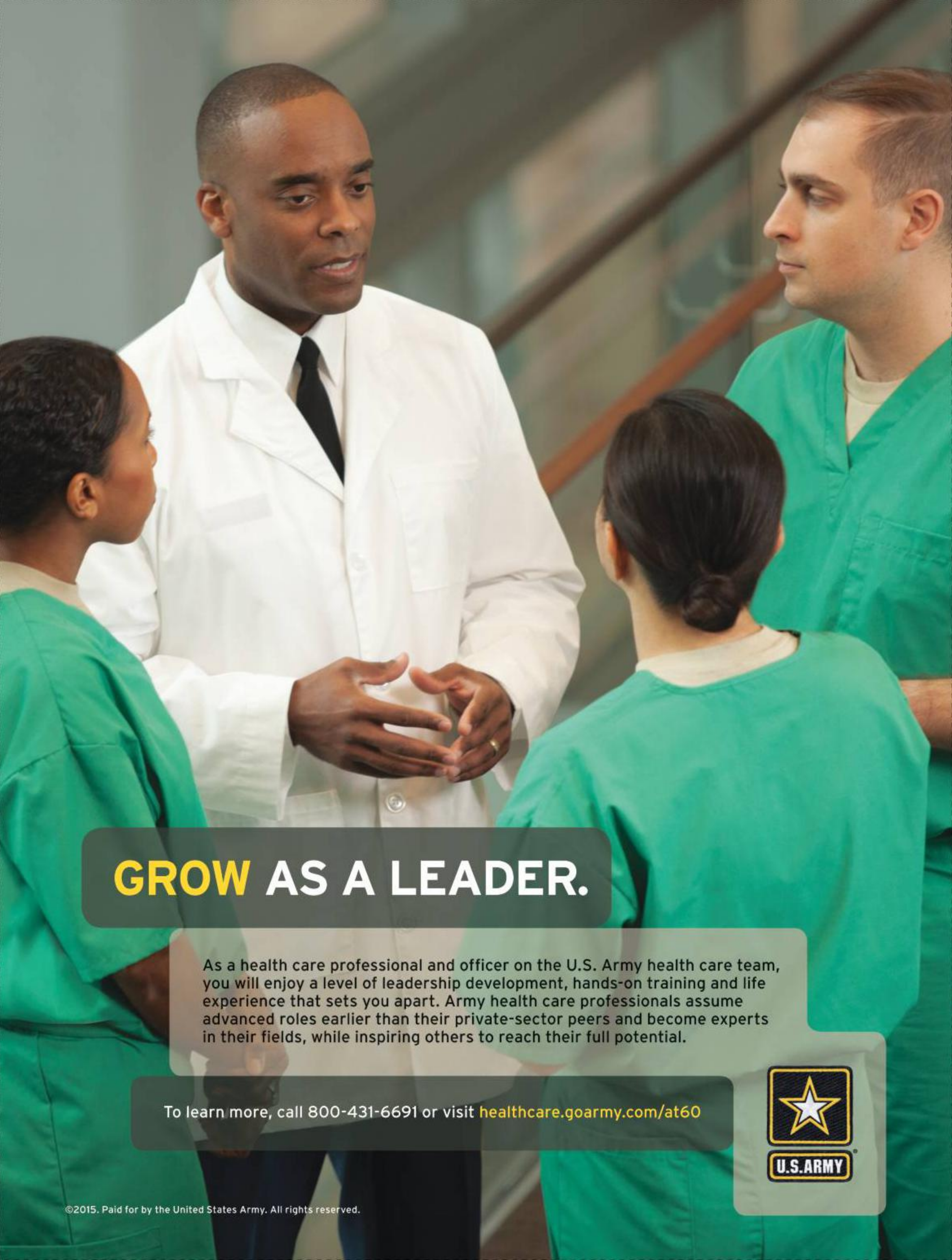
Developing countries are battling illnesses of the rich and poor

Life expectancy worldwide has risen for decades. But more people are living more years with debilitating ailments, according to a new study by the Institute for Health Metrics and Evaluation in Seattle. In developed countries (*top half of graphic*), the trouble comes almost entirely from noncommunicable conditions such as heart and lung disease and back pain (*orange*)—ills typically associated with lifestyle choices such as diet and exercise. In developing nations, however (*bottom*), the prevalence of these ailments is increasing rapidly, even as those countries continue to try to stamp out communicable diseases such as diarrhea and malaria that have plagued them for a long time (*blue*). If developing nations are clever, though, they can create health policies that impede the new threats and keep reducing the old ones. "Knowing what's coming," says Amy VanderZanden at the institute, "they can prioritize what they should do."

—Mark Fischetti

SOURCE: "GBD COMPARE." INSTITUTE FOR HEALTH METRICS AND EVALUATION, SEATTLE, WA, 2015. ACCESSED DECEMBER 1, 2015 *http://vizhub.healthdata.org/gbd-compare*

Graphic by Pitch Interactive


GROW AS A LEADER.
As a health care professional and officer on the U.S. Army health care team, you will enjoy a level of leadership development, hands-on training and life experience that sets you apart. Army health care professionals assume advanced roles earlier than their private-sector peers and become experts in their fields, while inspiring others to reach their full potential.
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