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JANUARY 2016
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The Brain's GPS

Pathfinding networks tell us where we are—and help to form new memories

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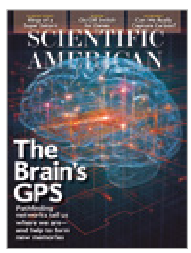

ON THE COVER
Nobel Prize–winning research has identified the existence of brain regions that work together to function as a biological GPS. This neural navigation system deep within the brain allows us to move seamlessly from place to place. The disorientation that afflicts Alzheimer's patients may result if these cerebral areas are damaged. Illustration by Mark Ross.

Photograph by Jeff Wilson

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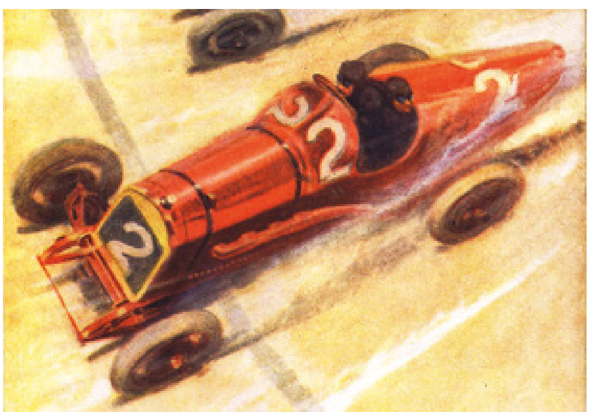

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ON THE WEB

2015 Breakthrough Prizes
Scientific American spotlights the winners' outstanding achievements in life sciences, physics and mathematics.
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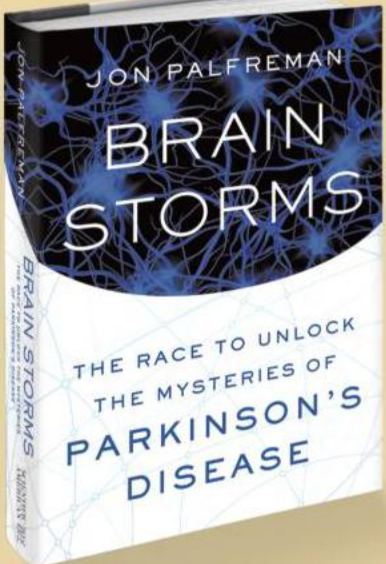
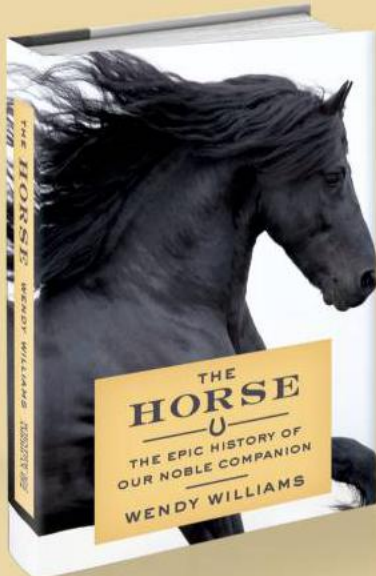
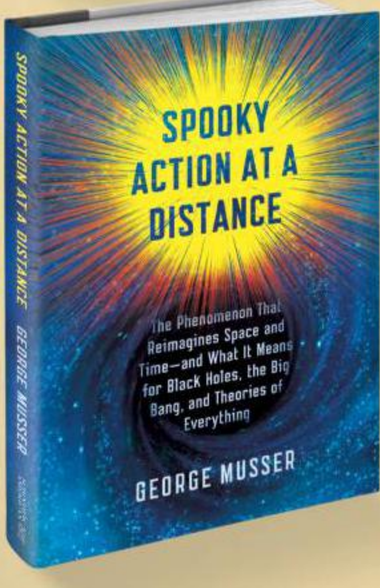
NEW BOOKS FOR THE NEW YEAR



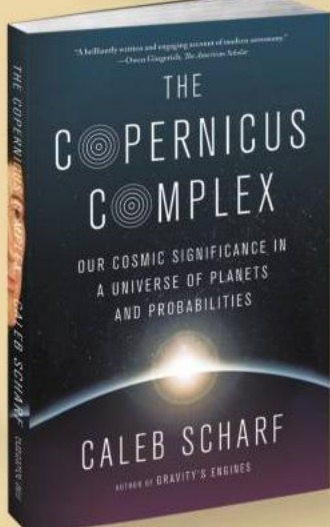
"[Palfreman] has a gift of explaining complex molecular processes in clear, understandable terms. What is ultimately appealing is the 'just-around-the-corner' prospect of solving this mystery—making you marvel at what is possible."
—David Takami, *The Seattle Times*



"Charming and deeply interesting . . . Few writers manage to capture the magic of [the] extraordinary relationship [between horse and human] as Ms. Williams does . . . I have read many books and articles on horses, but this must surely rank among the very best."
—Pat Shipman, *The Wall Street Journal*



"A highly enjoyable tour-de-force . . . Amid the superb writing here is a lot of information that will bring you up to date on everything you should know about this compelling mystery . . . This book will be one of the reading highlights of your year."
—David Eicher, *Astronomy*



"An intoxicating collection of questions answered with other questions, and startling discoveries that make creation even more mysterious . . . Books such as these remind us that we are lucky to be here at all, and even luckier to be here now."
—Tim Radford, *The Guardian*

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FROM THE EDITOR

Mariette DiChristina is editor in chief of *Scientific American*. Follow her on Twitter @mdichristina

Finding Our Place

Where am I going? As you'll learn in this issue, the way the brain processes the straightforward, location-based meaning of that question is just as interesting as its ability to ruminate on the existential meaning of the phrase. Our brain has a GPS-like system that senses where we are and where we are headed. It also factors in the passage of time in its calculations of position, doing so with an ease that leaves us barely aware of the effort. The processing occurs in networks of cells deep within the brain, which collaborate to create a mental map of our environment. These maps take the form of patterns of electrical activity that fire in a way that echoes the shape of the surrounding layout and our position in it.

Intriguingly, these pathfinding regions of the brain are involved in the making of new memories. Unforgivably, perhaps, my own brain has just suggested to me that this fact puts a new twist on the phrase "a stroll down memory lane." Nobel Prize–winning neuroscientists May-Britt Moser and Edvard I. Moser explore the terrain further in our cover story, "Where Am I? Where Am I Going?" The article starts on page 26.

Unfortunately, carbon emissions are headed in only one direction—up. With Paris climate talks drawing attention to the problem of excess carbon in the atmosphere from fossil-fuel burning, many have pointed to the need for carbon capture and storage. But can we afford it? In "The Carbon Capture Fallacy," senior reporter David Biello takes a look at a case in point: the building of the enormous Kemper "clean coal" power plant in Mississippi, which is intended to generate energy from the dirtiest form of coal while siphoning off the emissions. The captured carbon dioxide would, in turn, be pumped into oil wells to force out more oil. Kemper is turning out to be expensive—and costs have led to the shutdowns of more than a couple of dozen such plants. Can we find a way forward? Turn to page 58.

Shifting our focus to other worlds, we can soar through the magazine to the article "Rings of a Super Saturn," by astronomer Matthew Kenworthy, beginning on page 34. Think of Saturn, our solar system's second-largest planet—nearly 10 times the width of Earth—and its graceful rings. Now try to imagine what astronomers have found: a ring system some 200 times larger, around a giant planet orbiting a distant star in our Milky Way galaxy. This exoplanet may even have the first moon detected outside our solar system. These and other wonders await in this month's edition. ■

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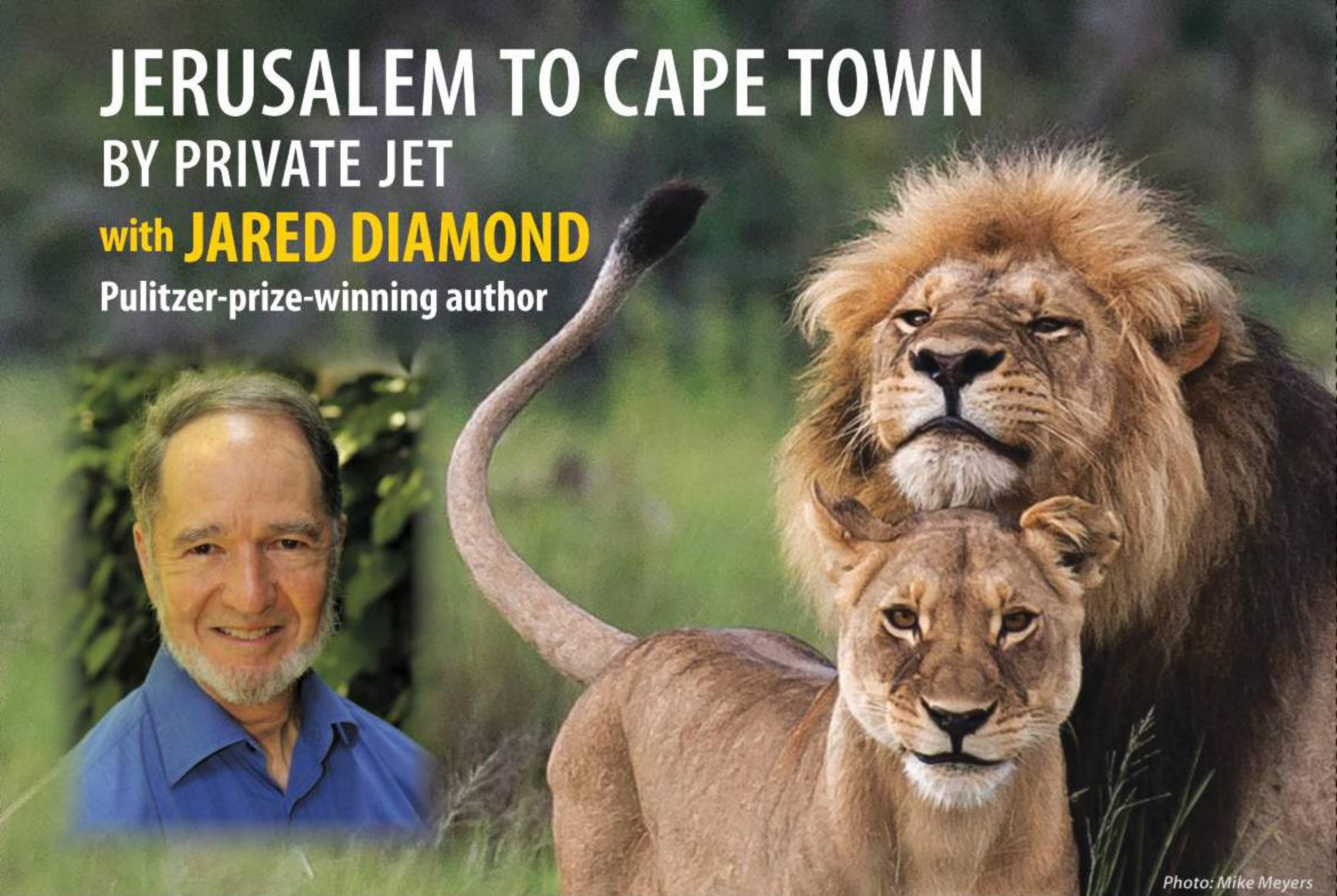

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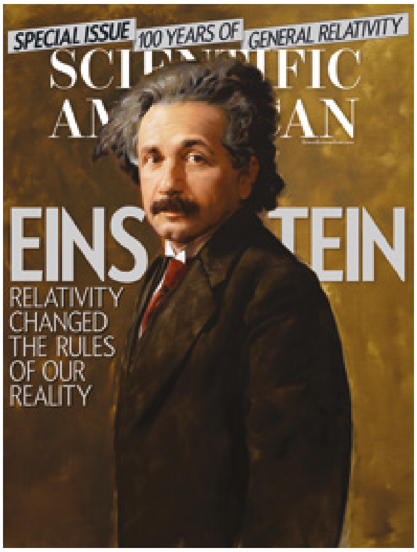

September 2015

CELEBRATING EINSTEIN

The opportunities for groundbreaking new discoveries as profound as those of Albert Einstein, whose achievements were documented in your September issue, have diminished. The review and approval processes for obtaining research funding from the federal government are not friendly to new ideas and approaches. Those who have demonstrated high levels of skill and creativity should be given more freedom to explore innovative approaches approved by a review system that does not eat up half their careers in chasing funding.

Thomas M. Vogt
Laguna Woods, Calif.

I was surprised to find no mention of the only practical application of Einstein's general theory of relativity, the Global Positioning System (GPS).

Around 1966 I worked at Aerospace Corporation in El Segundo, Calif. Part of my job was applying general relativity to correct the rates of the clocks that were to be launched into orbit.

The work was classified at the time, but I did publish a sanitized version in a physics journal. Civilian handheld GPS receivers became available many years later, and I was finally able to tell my wife what I had been up to!

W. J. Cocke
Professor emeritus
University of Arizona

"The processes for obtaining research funding from the federal government are not friendly to new ideas and approaches."

THOMAS M. VOGT
LAGUNA WOODS, CALIF.

FREE WILL VS. DETERMINISM

Toward the end of "Is the Cosmos Random?" George Musser makes a case for the existence of free will that ignores the following evidence against it: Some people would pay to do what others wouldn't do, no matter how much you paid them. People don't suddenly drastically change their personalities. And their preferences control everything they do.

Stanley Becker
via e-mail

MUSSER REPLIES: One might argue that our preferences constitute our will, and therefore if we act on the basis of those preferences, we act freely. In a sense, free will requires determinism, in that your acts are determined by you. When our actions don't align with our desires because of some kind of compulsion, we have lost our free will.

TIME TRAVEL

"A Brief History of Time Travel," by Tim Folger, gives a scenario in which an astronaut traveling 1,040 light-years at near the speed of light ages just 10 years while Earth ages 1,000 years.

Given that the human heart will beat only so many times in a person's lifetime, how can the astronaut age only 10 years?

Carol and Chas Sutherland
via e-mail

FOLGER REPLIES: The time dilation of special relativity affects all clocks, even biological ones. So an astronaut traveling at the speed of light does age more slowly—as seen by some stationary observer. The astronaut herself will not notice anything unusual—she will age at the normal rate.

SHOULDERS OF GIANTS

In "Cleaning Up after Einstein," by Corey S. Powell, there is a photograph of string theorists, including Leonard Susskind, at Stanford University. On the table are the three volumes of *The Feynman Lectures on Physics,* by Richard P. Feynman, Robert B. Leighton and Matthew Sands.

This is an elementary introduction to college physics. I cannot imagine that the researchers need to consult it at this stage of their careers and like to think that it was included as a homage to a great scientist.

I also spied a copy of *Gravitation,* by Charles W. Misner, Kip S. Thorne and John Archibald Wheeler (aka MTW). It's much more advanced, but again, I suspect the motive for its inclusion was homage.

Ronald Levine
Berkeley, Calif.

SUSSKIND REPLIES: If I recall, the photographer suggested that we place a few of the books that I use most often where they could be seen. Feynman's books may have been intended for a freshman class, but the insights are very subtle. If you are confused about a subject in physics, the first place to go is Feynman. If the subject is gravitation, then the second is MTW.

IMPROVING FORENSICS

In "Forensic Pseudoscience" [Skeptic], Michael Shermer claims that the AAAS Forensic Science Research Evaluation Workshop held last May demonstrated that "many fields in the forensic sciences … employ unreliable or untested techniques."

Flawed science is not unique to the field, but it is important to discuss it when it happens. The workshop highlighted some areas that have been recognized as problematic, but this is far from an indictment of all forensic science. We forensic scientists are grappling now with the implications of cognitive bias, and significant progress has been made in the field. It seems indisputable that forensic science is doing more to help convict the guilty and exonerate the innocent than the reverse.

Victor W. Weedn
Department of Forensic Sciences
George Washington University

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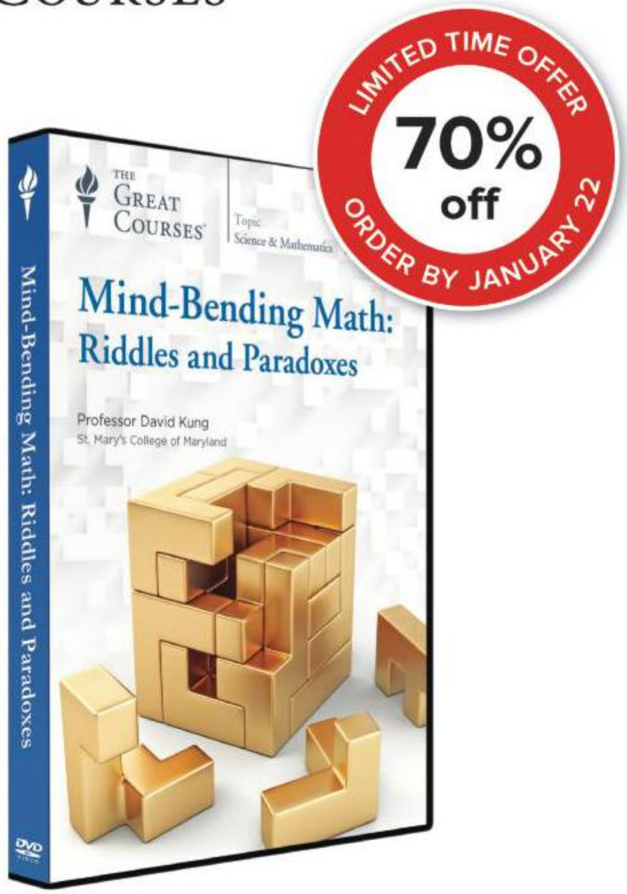

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SHERMER REPLIES: That forensic scientists are turning a skeptical eye toward their own practices is good to hear, but I find Weedn's final proclamation to be quite disputable. At the workshop I attended, I was told by a number of forensic scientists that no one knows how many innocent people are rotting in jail because of forensic pseudoscience. What to do about the wrongly convicted? Those who were convicted on, say, bogus arson pseudoscience should be set free. Will the leading forensic science organizations stand up for them?

HOLE HISTORY

In "Don't Blind NASA to Earth's Climate" [Science Agenda], the editors refer to NASA as having "spotted a dangerous, growing hole" in the ozone layer in the 1980s.

I thought that the discoverers of the ozone hole were scientists from the British Antarctic Survey, who reported it in *Nature* in 1985.

Frederick Hartley
Hayes, England

THE EDITORS REPLY: The 1985 paper did document the existence of the ozone hole. But the disturbing fact that it was growing was chronicled by NASA during the next several years.

ERRATA

The issue's introduction, "Einstein," by the editors, states that Sir Arthur Eddington confirmed a prediction by Albert Einstein that starlight would bend as it passed the sun. Rather Einstein's prediction, confirmed by Eddington, was that it would bend twice as much as predicted by Newtonian physics.

In "What Einstein Got Wrong," Lawrence M. Krauss describes Einstein's erroneous initial calculation of light's deflection by gravity (which put the deflection at half its true value). The text says the error was made in 1912 and never published. Einstein did publish the error, in 1911. Also in Krauss's article, the box "Einstein's Blunders" has an incorrect illustration of Einstein's earlier and later conceptions of gravitational waves and a flawed description of the later conception. The corrected description and illustration can be seen at www.ScientificAmerican.com/sep2015/erratum.

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A Campaign to Cut Drug Prices

Presidential candidates need to address this painful problem, but some duck it

The average price of a new cancer drug now exceeds $100,000 a year. The patient does not pay the entire tab, but someone who needs a prescription can still spend $25,000, not reimbursed by health insurance. That steep copayment equals about half of what the typical U.S. household earns in a year.

It is not just new cancer therapies that bear stratospheric price tags. Last year Turing Pharmaceuticals, a New York City start-up, provoked widespread outrage after it bought a 62-year-old infectious disease drug called Daraprim and raised the price from $13.50 a pill to an astounding $750 a pill before agreeing to scale back the price slightly. Patients in the U.S. often pay much more than Europeans for older drugs—not just for new pharmaceuticals protected by patents. In the U.S., prescription drug spending increased 13.1 percent in 2014, the highest annual increase since 2003.

The president we elect in 2016 needs to bring these prices down. With the political primaries now at full tilt, sky-high prices at the pharmacy have drawn the attention of voters. Polls say that Democrats and Republicans want the government to take action on drug costs, but regulation-shy Republicans have more of a problem formulating coherent policy.

The leaders in the Democratic race—Hillary Clinton and Bernie Sanders—have set out detailed proposals with some ideas in common: both candidates want to empower Medicare to use its purchasing power to negotiate prices with drug companies to get the best deal. And both propose that patients should be able purchase lower-cost drugs from foreign pharmacies, an option currently denied them.

Republican candidates have mostly dodged the issue. During a primary debate in late October, retired neurosurgeon Ben Carson said, "Some people go overboard when it comes to trying to make profits" but then quickly added that more regulation is not the solution: "Government is not supposed to be in every aspect of our lives, and that's what has been the problem."

The Republicans are making a strategic error if they do not take this issue more seriously. In an April poll, the Kaiser Family Foundation reported that Republican voters viewed outsize drug prices as a more pressing concern than getting rid of Obamacare. In an August follow-up, Kaiser found that three quarters of Republicans surveyed wanted Medicare involved in trying to obtain more reasonable prices from pharmaceutical companies.

The drug-pricing debate need not get bogged down in bickering about the merits of government regulation. Through long years of study, health care economists have mapped out policy options that are not inimical to market-based approaches to drug pricing. For example, Republican candidates could cite Switzerland as a model worthy of emulation: it first establishes a list of approved drugs and then sets a maximum price based on criteria such as R&D cost and effectiveness. But market forces—negotiations between a drug company and a private insurer—determine how much is charged up to the price ceiling.

At the very least, both Democrats and Republicans should prevail on drug companies for more transparency. Better data are needed to set better policy—and to evaluate claims by pharmaceutical companies that the billions spent to bring a new drug to market are justifiable. The candidates should also support laws or regulatory reforms at the national level that mirror bills that are making their way through legislatures in six states that require drug companies to provide more information about R&D and other expenditures.

If a just released drug can command the same price as a modest home in Oklahoma City, companies need to account openly for their costs and furnish some justification of the value that accrues to patients and insurers who foot the bill. And candidates from both parties need to pledge to make sure they do so. SA

SCIENTIFIC AMERICAN ONLINE
COMMENT ON THIS ARTICLE AT
SCIENTIFICAMERICAN.COM/JAN2016

Illustration by Celia Krampien

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Claire Pomeroy, M.D., M.B.A., is president of the Albert and Mary Lasker Foundation, dedicated to advancing medical research.

Academia's Gender Problem

To support women in science, we must reckon with a culture of unconscious bias

By Claire Pomeroy

Last October news broke of allegations that University of California, Berkeley, astronomer Geoff Marcy had for years harassed female students. (Marcy, who denied some of the allegations, resigned.) The news reminded me of an experience I had in school. I admired an instructor and was honored when he took me out for a celebratory dinner near the end of the course. After walking me home, he put his arms around me, and alarm bells began to ring. When I rebuffed the advance, he complied, but later my grade changed from "outstanding" to "pass." It was a painful lesson, and I never spoke about it to anyone.

I went on to complete my training in internal medicine and infectious diseases and embarked on a career as an HIV physician. I conducted research on virus-induced immunosuppression under the tutelage of two outstanding male professors. I felt supported by my mentors, usually men, who nurtured my clinical and research paths. But even as my career progressed, I observed that many of my female colleagues were disproportionately dropping out of academic medicine careers.

The statistics bore out my hunch. Although the percentage of doctorates awarded to women in life sciences increased from 15 to 52 percent between 1969 and 2009, only about a third of assistant professors and less than a fifth of full professors in biology-related fields in 2009 were female. Women make up only 15 percent of permanent department chairs in medical schools and barely 16 percent of medical school deans. The pipeline to leadership is leaking.

The problem is not only outright sexual harassment—it is a culture of exclusion and unconscious bias that leaves many women feeling demoralized, marginalized and unsure. In one study, science faculty were given identical résumés in which the names and genders of two applicants were swapped; both male *and* female faculty judged the male applicant to be more competent and offered him a higher salary.

Unconscious bias also appears in the form of "microassaults" that women scientists are forced to endure daily. This is the endless barrage of purportedly insignificant sexist jokes, insults and put-downs that accumulate over the years and undermine confidence and ambition. Each time it is assumed that the only woman in the lab group will play the role of recording secretary, each time a research plan becomes finalized in the men's lavatory between conference sessions, each time a woman is not invited to go out for a beer after the plenary lecture to talk shop, the damage is reinforced.

When I speak to groups of women scientists, I often ask them if they have ever been in a meeting where they made a recommendation, had it ignored, and then heard a man receive praise and support for making the same point a few minutes later. Each time the majority of women in the audience raise their hands. Microassaults are especially damaging when they come from a high school science teacher, college mentor, university dean or a member of the scientific elite who has been awarded a prestigious prize—the very people who should be inspiring and supporting the next generation of scientists.

If we are to achieve the full promise of science and medicine, we must use all the brainpower available to us by ensuring the full participation of women. We must reprimand blatant harassment, but we must do much more than that. We must change the culture of our organizations so that women feel the value they bring to science will be encouraged and celebrated. SA

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ADVANCES

Although NASA has found the largest asteroids in Earth's vicinity, millions of smaller ones that could also threaten our world remain uncatalogued.

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INSIDE

- The rudimentary politics of ruminants
- The man who climbs trees for a living
- Why bankers lose their sense of self
- How "brainprints" can identify an individual out of a crowd with 99 percent accuracy

SPACE

Fear of the Unknown

NASA's best hope for planetary defense resides with a proposed asteroid-seeking space telescope. Will it be funded?

Before it became a crater of saurian doom, the space rock that ended the age of the dinosaurs most likely was a near-Earth object (NEO), an asteroid that occasionally came within striking distance of our planet as it orbited the sun. NASA and other space agencies are now developing ways to deflect and redirect asteroids should they approach, but those techniques will be useful only if we find dangerous NEOs before they find us. Yet NASA's search is not going as planned.

In 2010 NASA completed a congressionally mandated inventory of more than 90 percent of NEOs with a diameter of one kilometer or greater—objects that are big enough to create a planetary-scale disaster. No known objects of such cataclysmic size are now on collision courses with Earth, but smaller NEOs are still out there undiscovered by the millions. Even puny ones can cause big regional problems, such as the 18-meter rock that exploded over the Russian city of Chelyabinsk in 2013, inflicting more than $30 million in damage and injuring at least 1,600 people.

Recognizing the threat of smaller NEOs, in 2005 Congress upped the ante for NASA, giving the agency until 2020 to catalogue 90 percent of midsized NEOs at or above 140 meters in diameter. Congress, however, failed to provide the agency with sufficient

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new funding to achieve this ambitious goal.

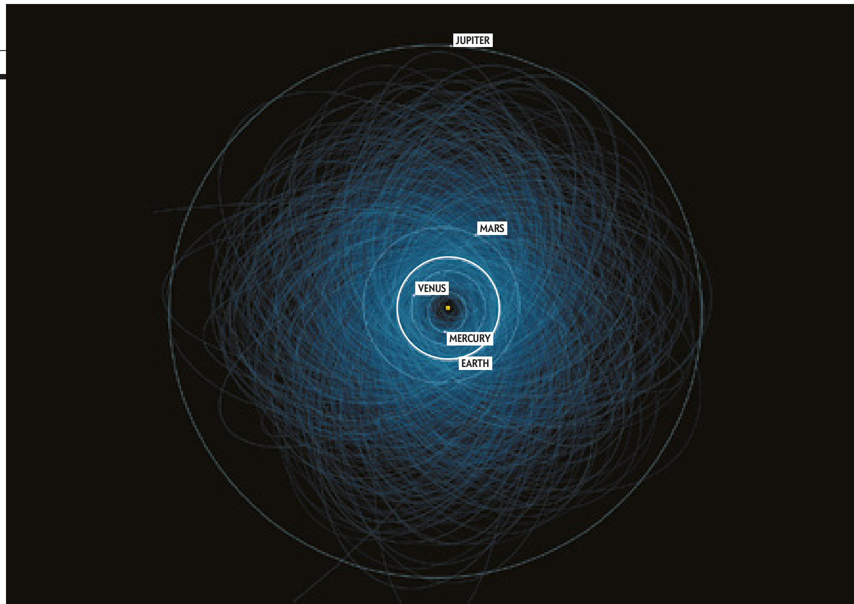
So NASA is far behind. "With the current capabilities we have, the deadline of 2020 is not achievable," says Lindley Johnson, program officer for NASA's NEO survey. The agency largely relies on three ground-based optical telescopes to hunt for NEOs—objects that, even at their largest and closest, are still very dim and difficult to find. This approach limits the search to hours when the skies above the observatories are dark and clear. NASA's Wide-field Infrared Survey Explorer (WISE) spacecraft also hunts NEOs by looking for their telltale thermal glow as they are warmed by sunlight, but WISE is predicted to cease functioning as early as 2017.

All these limitations mean that the present survey would require another 30 to 35 years to find the several tens of thousands of midsized NEOs estimated to lurk undetected in the solar system. "There are no penalties for missing the deadline," Johnson says, "so long as there's nothing big out there that's going to hit us."

Now the best hope for global asteroid awareness may be a proposed infrared space telescope called NEOCam, which the agency short-listed in September 2015, along with four other proposals competing for funding as part of its Discovery program of highly focused science missions. NASA will select one or two of those proposals later this year for continued development toward a launch as early as 2020.

If flown, NEOCam would use innovative new infrared detectors to discover 10 times more NEOs than all those found to date, fulfilling Congress's 2005 mandate. But NEOCam's selection is not a foregone conclusion. In the high-stakes environment of federally funded space science, it could be argued that the money for a mission to seek out dangerous space rocks should come from somewhere besides NASA's planetary science division, which has been a regular target for cuts in recent federal budgets. Although Congress recently increased the financial support for the NEO survey from $4 million a year to $40 million, the price tag for a space mission to hunt for midsized objects is estimated to be about half a billion dollars. So without another big boost to the NEO program's funding, there is nowhere else within NASA that the money can easily come from except for the agency's planetary science programs.

The struggle for money is not a problem that should even exist, says Michael A'Hearn,



As of early 2013, NASA had mapped about 1,400 "potentially hazardous asteroids." None are labeled worrisome for the next 100 years.

PRECEDING PAGES: ANDRZEJ WOJCICKI *Science Source*; THIS PAGE: COURTESY OF NASA AND JPL-CALTECH

BY THE NUMBERS

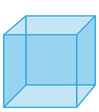
Soaked in Space

Our solar system is overflowing with liquid water

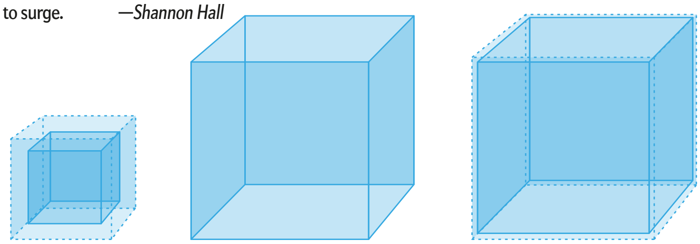
In early 2015 astronomers spotted water vapor shooting out of cracks on Saturn's moon Enceladus, confirming long-held suspicions of an ocean of liquid water deep beneath the ice. Soon after, a separate team saw signs of an ocean sloshing within Ganymede, the largest of Jupiter's icy moons. More recently, NASA presented the best evidence yet for liquid water on Mars. It now looks like the solar system is awash with this key ingredient for life. A total volumetric estimate of the confirmed oceans alone adds up to 50 times more water than is found on Earth—a figure that could continue to surge. —*Shannon Hall*

Total volume of water on Earth:

1.3 billion cubic kilometers



Number of times the amount of water on Earth estimated for each moon:



Europa: **1–3**

Titan: **13**

Callisto: **12–14**

COMMENT AT ScientificAmerican.com/jan2016

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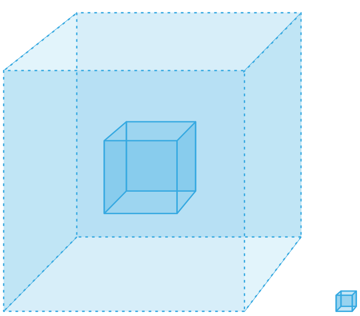
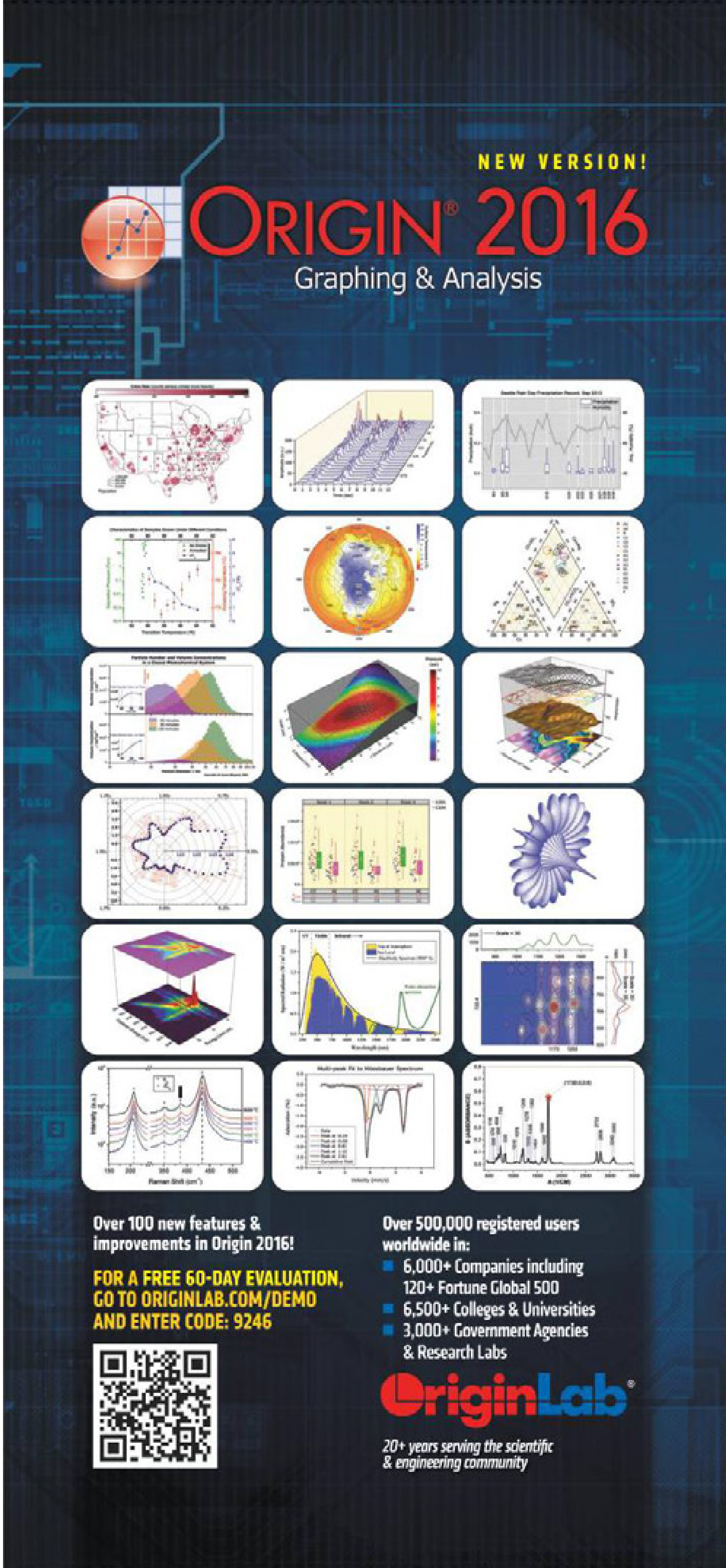
an astronomer at the University of Maryland and former principal investigator for NASA's Deep Impact spacecraft, a Discovery-class mission. Given that Congress considers the search an important public policy task for NASA, it should appropriately fund the mission itself, he explains: "Can NASA afford not to select NEOCam? That is precisely what I worry about."

Amy Mainzer, an astronomer at the NASA Jet Propulsion Laboratory and NEOCam's principal investigator, emphasizes that the mission is an excellent candidate for the Discovery program because it has scientific objectives that go beyond protecting Earth from asteroids. For example, the telescope would characterize the orbits, shapes, compositions and spin rates of some near-Earth objects—information that would help researchers trace the history of the solar system as well as select new targets for future human and robotic deep-space missions.

But even if NEOCam was purely about planetary defense, it or another mission like it still would be worthwhile, Mainzer maintains. "In terms of risk versus consequences, the possibility of an asteroid strike isn't as worrisome as something like climate change, which is very real and must be addressed right away," she says. "But this doesn't mean we shouldn't go out and look for potentially hazardous NEOs. Looking will go a long way toward quantifying what we're dealing with and how worried we should be. It's a reasonable thing to do." —*Lee Billings*



Graphic by Amanda Montañez



COURTESY OF QUEENSLAND UNIVERSITY OF TECHNOLOGY

ECOLOGY

The Starfish Assassin

A poison-carrying robot homes in on starfish that are destroying the world's most famous coral reef

The Great Barrier Reef will have a robotic protector beginning this winter. The underwater autonomous vehicle is programmed to patrol the massive living structure in search of destructive crown-of-thorns starfish (COTS), which it then kills by lethal injection. These starfish prey on coral polyps, and although they are native to the reef, their population has exploded in the past few years, possibly because of overfishing of their natural predators. The latest report from Australia's Great Barrier Reef Marine Park Authority places the venomous invertebrates alongside climate change and human activity as a significant threat to the reef, which lost half its coral cover between 1985 and 2012.

COTSbot, developed by robotics researchers at Queensland University of Technology in Australia, could help slow the starfish's invasion. Artificially intelligent, it correctly identified its target 99.4 percent of the time in laboratory tests. "It's now so good it even ignores our 3-D-printed decoys and targets only live starfish," Queensland's Matthew Dunbabin says. A fleet of COTSbots could supplement the efforts of human divers who currently remove or poison the sea stars by hand and could operate during bad weather or high currents. They could also be useful at night when starfish are more active but swimming is prohibited. —*John R. Platt*

HOW IT WORKS

1. The COTSbot follows a preprogrammed path, moving up and down the Great Barrier Reef with the help of five thrusters. It stays close to the reef—and avoids bumping into the delicate structure—with the aid of sonar and multiple cameras.
2. The cameras scan for starfish, distinguished by their purplish colors, arm and thorn shapes, and creeping motion. Starfish often wrap around and hide under coral outcroppings, but the robot's software has been programmed to recognize those positions.
3. When the robot spots a crown-of-thorns starfish, its needle-capped pneumatic arm lowers and injects 10 milliliters of poisonous bile salts into the echinoderm. The compounds effectively digest the animal from the inside.
4. A poisoned starfish will die within 24 hours, leaving no opportunity for separation and regeneration—a survival tactic that is a boon for the starfish population but maddening to those trying to reduce its numbers.
5. The vehicle's tanks carry enough poison to kill more than 200 starfish in one four- to eight-hour mission. The rapid pace is key because even one starfish can spawn millions of young.

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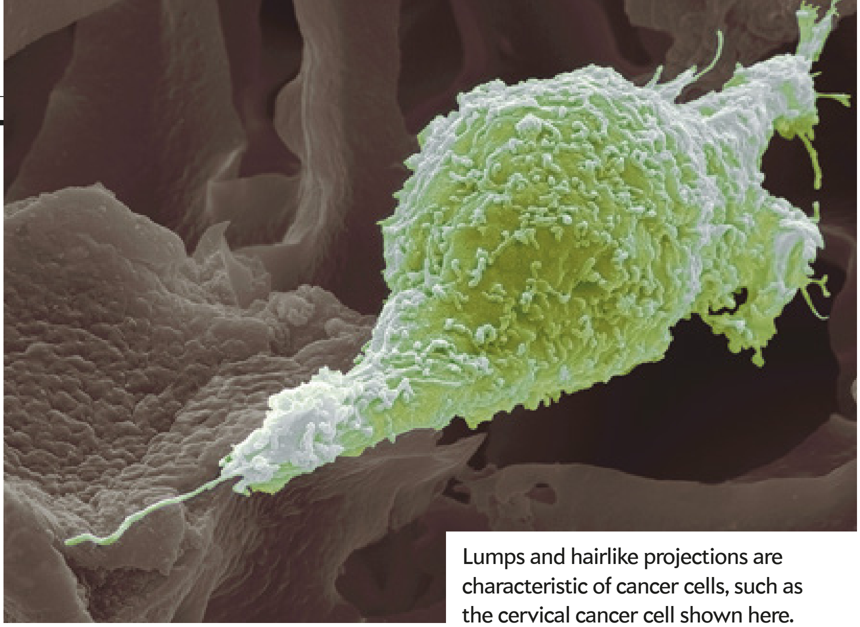

Lumps and hairlike projections are characteristic of cancer cells, such as the cervical cancer cell shown here.

STEVE GSCHMEISSNER *Science Source*

BIOLOGY

Divide or Conquer

Cancer can't proliferate and invade at the same time

The worst cancer cells don't sit still. Instead they metastasize—migrate from their original sites and establish new tumors in other parts of the body. Once a cancer spreads, it is harder to eliminate. A study by developmental biologists offers a fresh clue to how cancer cells acquire the ability to invade other tissues—a prerequisite for metastasis. It reveals that invasion requires cells to stop dividing. Therefore, the two processes—invasion and proliferation—are mutually exclusive. The finding could inform cancer therapies, which typically target rapidly proliferating cancer cells.

David Matus of Stony Brook University and David Sherwood of Duke University turned to a transparent worm to elucidate this invading process. During the worm's normal development, a cell known as the anchor cell breaks through a structure called the basement membrane, which initially separates the uterus from the vulva. The process is similar to how human cancer cells invade basement membranes to enter the bloodstream, which carries them to distant sites. So biologists have adopted *Caenorhabditis elegans* as a metastasis model organism, which they can easily image and genetically manipulate.

After turning on and off hundreds of genes in *C. elegans,* Matus's team found a gene that regulated anchor cell invasion. When it was turned off, the anchor cell failed to invade the basement membrane. But the anchor cell also did something unexpected: it began to divide. Conversely, when the researchers inhibited cell proliferation, the anchor cell stopped dividing and began to invade again. Further experiments showed that halting cell division was both necessary and sufficient for invasion. Although anecdotal observations by pathologists have suggested this either/or situation might be the case, the new study is the first to uncover the genetic mechanism that explains why these two processes must be mutually exclusive. The results were published in October in the journal *Developmental Cell.*

The study also explains the long-standing but mysterious observation by cancer biologists that the invading front of many tumors does not contain dividing cells; instead the invasive cells lead the dividing cells behind them and push forward into healthy tissue as the tumor grows in size. "This research changes how we think about cancer at some level," Matus says. "We think of cancer as a disease of uncontrolled cell division, and in fact, many cancer drugs are designed to target these dividing cells. But our study suggests that we need to figure out how to target these nondividing cells, too, as these are the ones that are invasive."

Before the insight makes its way into cancer treatments, however, it will need further testing. "Now we can take that simple model and go to more complex systems—like breast cancer tumors," says Andrew Ewald, a cancer cell biologist at Johns Hopkins University. Metastatic breast cancer alone accounts for about 40,000 deaths every year in the U.S., but the five-year survival rate is nearly 100 percent if caught before the cancer spreads. —*Viviane Callier*

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ANIMAL BEHAVIOR

Ballots for Bison

A bison herd moves in the direction chosen by most of its constituents

Every few years Americans in major cities elect a mayor. The process is relatively straightforward: we vote, and the candidate who carries the majority wins. The same goes for certain bovines. Ecologist Amandine Ramos of the French National Center for Scientific Research (CNRS) spent three months observing a bison herd at the Monts-d'Azur Biological Reserve, about 20 miles from Nice. It turns out that European bison operate by majority rule.

These individuals "cast a vote" for the direction they would like to move by orienting their bodies, Ramos observed. If they want to graze in a meadow, they face the meadow. If they would rather slake their thirst, they turn toward a water hole. Eventually one bison makes a move. If the initiator advances in the direction preferred by most herd members, the group follows. If the initiator chooses a less popular option, few follow, and the group might split for a brief period. Anyone can initiate a movement, although adult females typically garner the largest number of followers. In essence, the initiator with the most votes wins and ends up leading most of the herd. The study was published recently in the journal *Animal Behaviour*.

The findings could help wildlife managers reduce conflict among farmers and bison, which frequently raid crops. By outfitting those individuals likely to be leaders with collars that deliver a mild shock, managers may be able to effectively control an entire herd.

European bison are not the only nonhuman species that make decisions collectively. The behavior has also been observed in animals ranging from other ungulates such as African buffalo to primates such as Tonkean macaques. For Ramos, the study is a reminder that "communication and consensus are two processes that also exist in the animal kingdom." Democracy, or at least a form of it, is not unique to *Homo sapiens americanus.* —*Jason G. Goldman*

Locata's positioning system blankets the White Sands Missile Range. Two transmit antennas are shown above.

TECHNOLOGY

Ground Control

A new terrestrial network could eliminate GPS's blind spots

Anyone who has struggled to pinpoint his or her location in a mall, airport or urban canyon amid skyscrapers has experienced a GPS gap firsthand. In fact, the global positioning network is filled with them: buildings, jammers and the landscape itself can block a signal's path between GPS satellites and receivers in a smartphone or other digital device. Technologies such as Apple's iBeacon have attempted to fill in holes with linked sensors that track indoor location using Wi-Fi or Bluetooth, but a new ground-based system by Australian company Locata is the first to produce a signal that merges seamlessly with the GPS network. And it is incredibly accurate.

Conventional GPS determines location by measuring the time it takes for a signal to travel from a transmitting satellite in medium Earth orbit to a receiver. Three such readings from three separate satellites triangulate a location in 2-D space (longitude and latitude); a fourth signal lets the system assess 3-D space (altitude). Each satellite carries four atomic clocks that are synchronized twice daily with a master clock in Colorado Springs, Colo. The blind-spot problem presents itself simply: if a user moves out of the satellites' sight lines, the signal is lost.

Locata's system resolves this issue by layering in an independent network of transceivers that communicate over ground. A test last year in Washington, D.C., by the U.S. Naval Observatory, the division responsible for maintaining the GPS master clock, found that Locata's web of signals synced up within 200 trillionths of a second, more than 50 times faster than GPS. And unlike GPS, the signals are strong enough to pass through walls. "We're analogous to a Wi-Fi hotspot," explains Locata CEO and co-founder Nunzio Gambale, who has been designing the system for some 20 years.

The system most likely is a decade from the consumer market but has proved successful so far in commercial partnerships, including a recent deal with the NASA Langley Research Center, where the technology assists tests of unmanned aircraft safety systems. Locata networks also have helped assess the efficacy of vehicle crash-avoidance systems at the Insurance Institute for Highway Safety and have been used to monitor U.S. Air Force aircraft locations at the White Sands Missile Range in New Mexico, where GPS is currently jammed to simulate warfare environments.

Ideally Locata transceivers would be integrated into all cellular towers, bringing centimeter-level location accuracy to everyday consumers, Gambale says. And receivers eventually will be small enough to embed in smartphones and thousands of other connected devices, ranging from watches to dog tags to self-driving cars. "The next-generation systems need a lot of synchronization," he says. "So the Internet of Things, which is inevitable and coming, raises the bar enormously." —*Corinne Iozzio*

JAMES BALOG *Getty Images* (*bison*); COURTESY OF LOCATA (*GPS*)

COMMENT AT ScientificAmerican.com/jan2016

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Q&A

Branches of Science

When researchers need to gather canopy data, they call Tim Kovar

COURTESY OF STEVE LILLEGREN

Tim Kovar climbed his first tree in his Nebraska backyard at the age of four. Now a master climbing instructor, he has scaled more than 5,000 trees worldwide, at sites ranging from South America to Southeast Asia and in every U.S. state except Alaska. Many of those trips were organized by biologists, entomologists and other scientists who hired Kovar to gather treetop data or to set up rigs for safe ascents. He has taught close to 1,000 researchers how to climb trees, assisted more than two dozen of them at their field sites and been acknowledged in a textbook about at-risk treetops. When not assisting with scientific studies, Kovar can be found in Oregon City, Ore., teaching researchers, elementary school students, the elderly and everyone in between how to climb trees at his school, Tree Climbing Planet. Edited excerpts follow.

—*Interview by Rachel Nuwer*

What is the most challenging aspect of climbing trees?

Technical tree climbing involves a rope, saddle and other proper tree-climbing gear because you're actually climbing on the rope rather than on branches. Getting the rope in place is usually the hardest part. For most trees in temperate forests, you can throw the first line up, but for really tall trees in tropical forests, you need to use a slingshot or a bow and arrow. It once took me three days to set a rope in a giant ceiba tree in Panama.

Have you ever been in danger while up in a tree?

In the tropics, as much as 90 percent of animal life occurs in the canopy. Ants, scorpions, spiders and snakes live in the branches and use them as highways. I was once 140 feet up a tree in the Brazilian Amazon when a swarm of bees flew in. I've also had thousands of ants crawl down my climbing rope. When that happens, all you can do is descend.

Why do scientists call you?

I'm not a scientist, but the cool thing about my job is that I get to travel with them to remote places, such as the Western Ghats in India. A lot of novice researchers can go straight up a rope, but they don't know how to go farther out onto the branches. I help them. For example, I've been in the field with canopy researcher Soubdra Devy, and I partner up with Meg Lowman, also known as the real-life Lorax, at least once a year, usually for a citizen science project. I also work with scientists doing outreach: I've brought kids into Monterey cypress trees to collect lichen samples.

Have you collected data yourself?

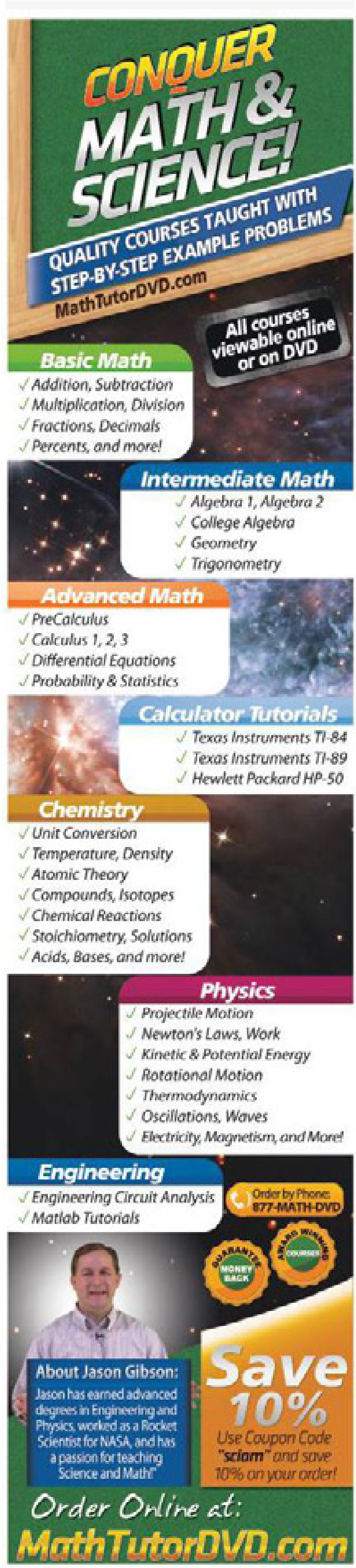
I've made tree measurements, gathered aerial soil, collected fruit and searched for red tree voles. I also went out with some herpetologists in India to find king cobras in the trees. Lucky for me, we were not successful (I have a mild fear of snakes).

What's your next adventure?

This winter I'll be in Monteverde, Costa Rica, teaching researchers about aerial-rescue techniques in tropical environments. I'll also be joining the North Carolina Urban/Suburban Bear Study group, which will be accessing trees that bears den up in for the winter.

What's your favorite type of tree to climb?

Getting 40 feet into an oak tree, putting up a hammock and just chilling out gives me a much deeper connection to nature. That's what I like to call tree time.



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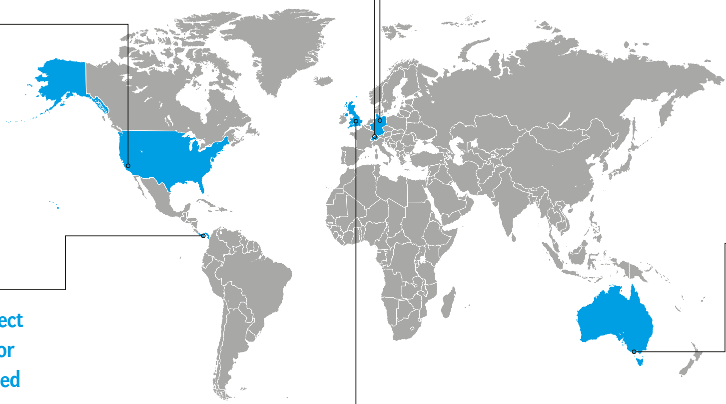
IN THE NEWS

Quick Hits

SWITZERLAND
Roboticists in Zurich debuted an autonomous robot that lays bricks in preprogrammed structures. Its inventors suggest the bot could become a fixture at construction sites.

GERMANY
This month Volkswagen will begin to recall at least 11 million diesel cars that emit more pollutants than regulations permit. The company is offering cash to owners in the U.S. market.

U.S.
As of January 1, California retailers are prohibited from selling showerheads, toilets, faucets and appliances that do not pass new efficiency standards for reducing water use.



PANAMA
An eight-year-long expansion project of the Panama Canal is scheduled for completion early this year. The added width will allow larger ships to pass through and accommodate twice the volume of traffic.

U.K.
The world's largest clinical trial is now under way. It will monitor 11,000 patients for as long as 12 years to investigate whether taking aspirin daily stops the recurrence of some cancers, including stomach and breast cancer.

AUSTRALIA
On an island off the state of Victoria, government-approved sheepdogs now protect wild penguins from preying foxes. A new trial will see if the canines can do the same for dwindling numbers of bandicoots.

For more details, visit
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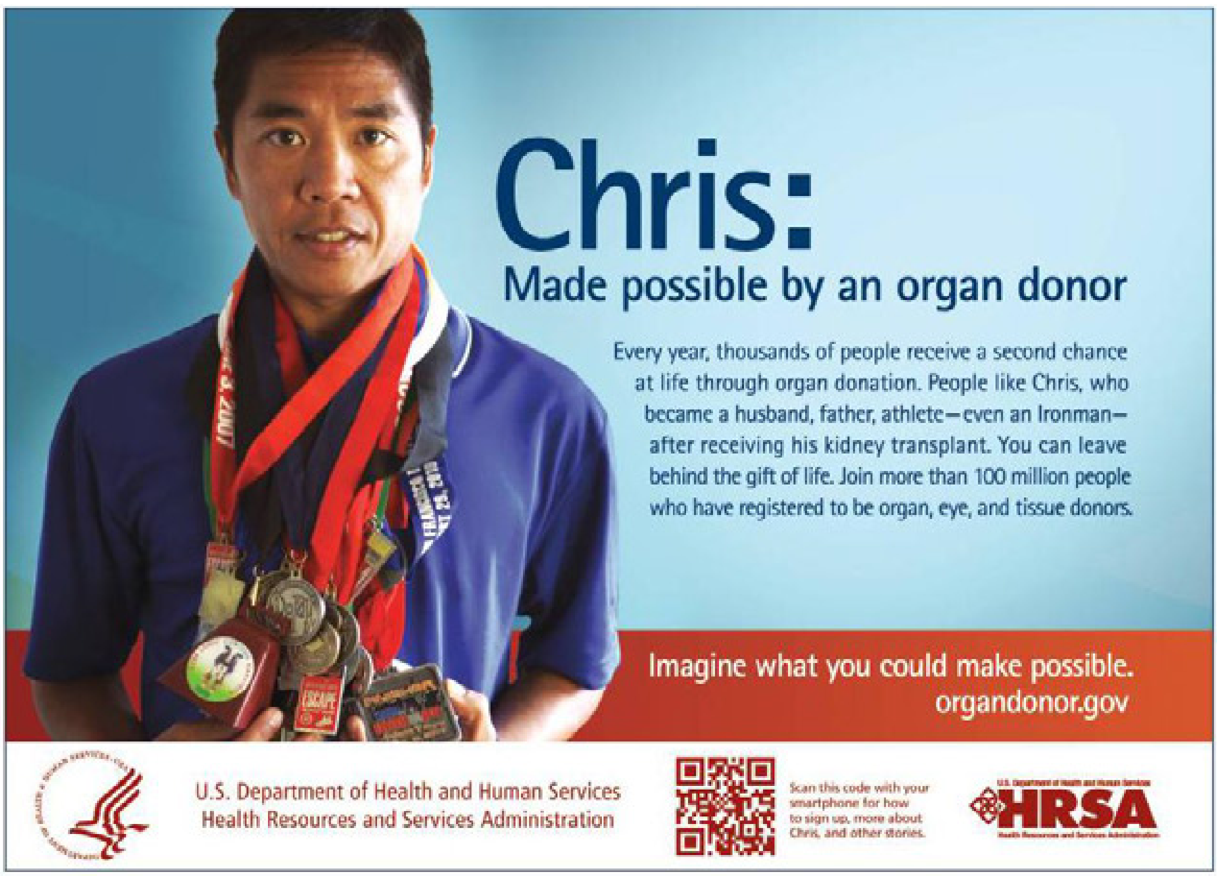

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PSYCHOLOGY

Frictionless Finance

Nothing sticks on a banker—not even his or her identity

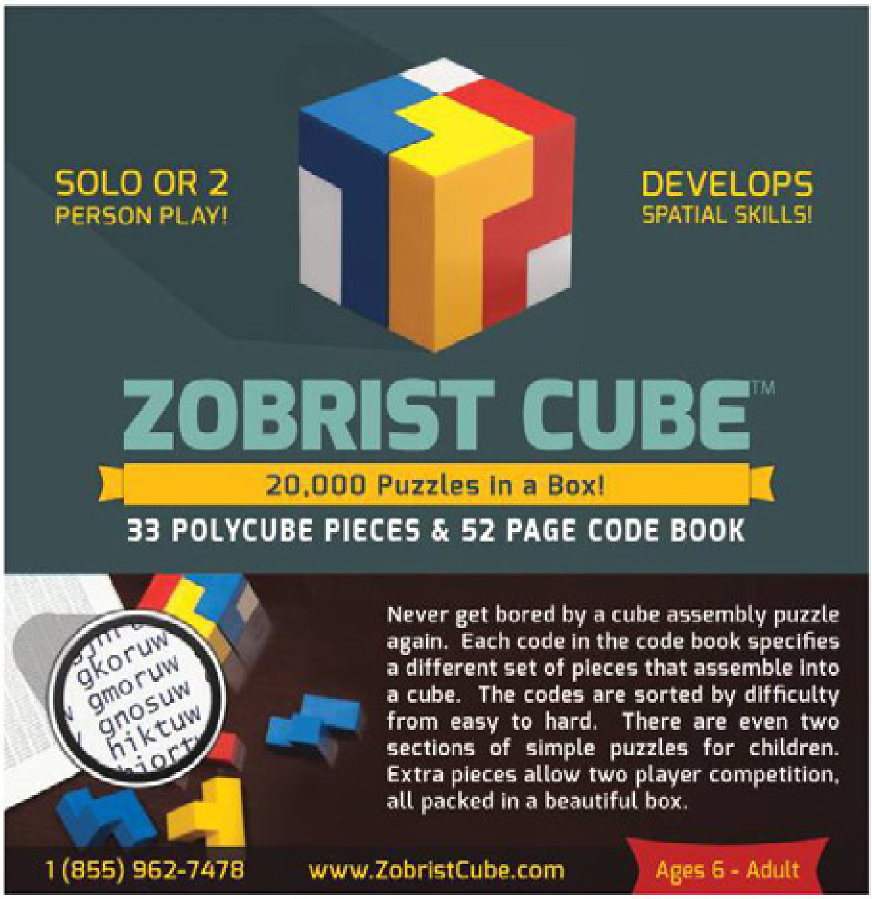
For most people, identity is inextricably tied to work. We strive for meaning within our jobs and take criticism of our labors personally. Not so for senior investment bankers. They dissociate their sense of self so severely from their work that researchers have coined a new term for the phenomenon: teflonic identity maneuvering.

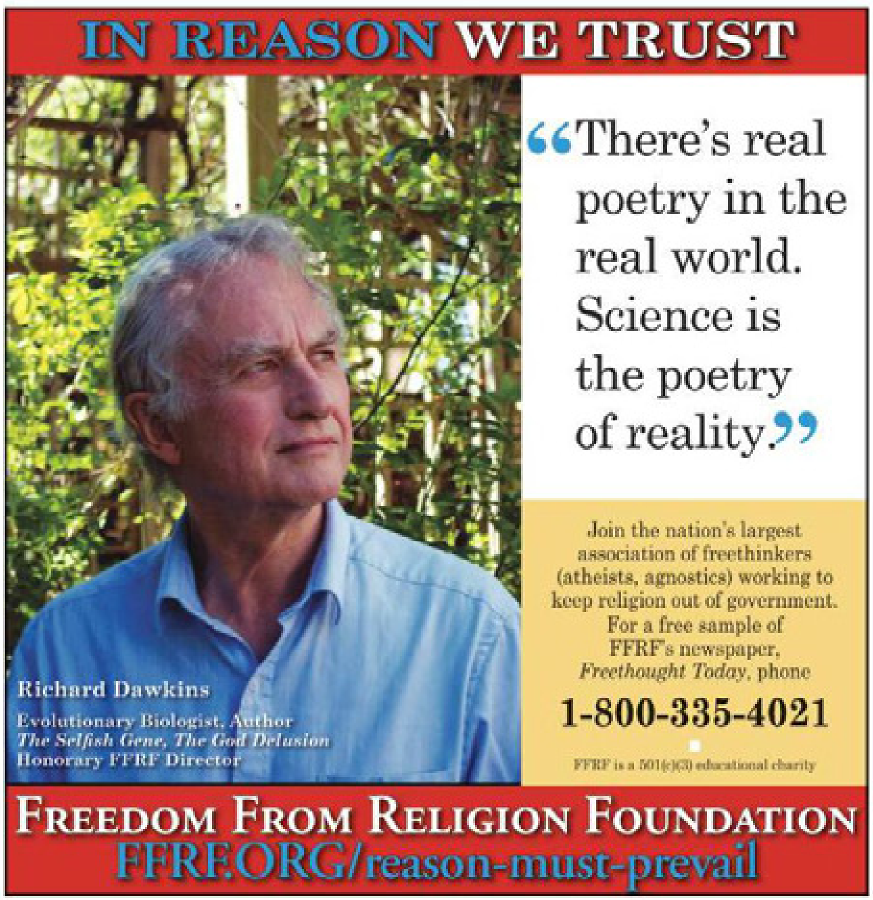
The inspiration for the nomenclature followed a series of in-depth interviews conducted over nearly two years with six senior investment bankers in London. All the subjects described situations in which they regularly circumvented or avoided deriving a sense of identity at work. For example, in one interview, a banker said of his explosive boss: "I am kind of used to it now, and it just washes over me.… I just see it as my job and don't take anything personally."

Such mental maneuvering may come in response to the demanding and exploitative environment that prevails in the banking sector, says Maxine Robertson, who worked on the study and is a professor of innovation and organization at Queen Mary, University of London. The minimization of self could serve as a coping mechanism. The participants justified this psychological detachment by the amount of money they made, according to findings published in the journal *Organization Studies.*

Alden Cass, a New York City–based clinical psychologist who was not involved in the study, worries about the long-term psychological cost. When people put money before mental health, he says, they risk burnout, physical ailments, substance-abuse problems and divorce.

With few participants, the study may not apply to other types of bankers. But it is notable, given a paucity of research on the lack of identity. The authors now wonder if teflonic identity maneuvering appears in other high-stress environments, such as academia. —*Shannon Hall*





Illustrations by Thomas Fuchs

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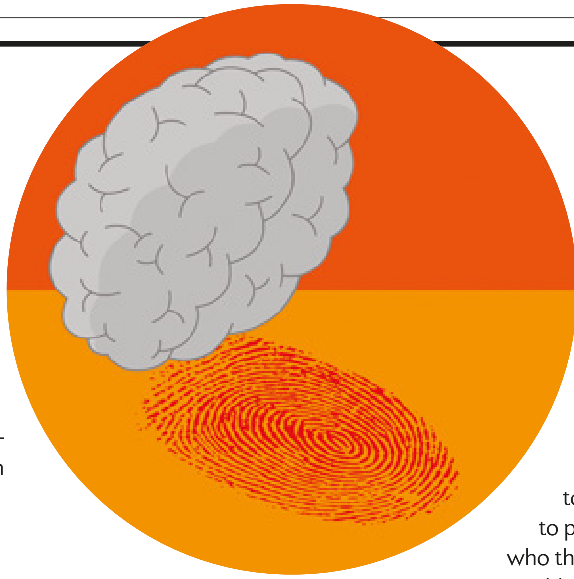
NEUROSCIENCE

The Brain's Whorl

A scanning technique can pinpoint individual "brainprints"



We all suspect we're unique, and methods for identifying individuals, whether by examining fingerprints or strands of DNA, confirm this conviction. A recent study shows that each person's mind also exhibits a distinct pattern that could be used as a distinguishing feature with near-perfect accuracy.

The researchers, led by Emily Finn of Yale University, relied on functional connectivity MRI (fcMRI) to examine brain activity in 126 healthy young adults. A "connectivity profile" was then created for each subject based on an estimate of the strength of connections between every pair of nodes in a network of 268, representing various brain regions. These fingerprintlike profiles identified participants with 94 percent accuracy.

The team then looked at groups of nodes that correspond with networks dedicated to visual, motor or other tasks to see if some networks contributed more to individuality than others. The frontoparietal network, involved in focusing our attention, performed best, allowing the group to identify individuals with 99 percent accuracy. This recently evolved network is thought to be sensitive to one's experience, whereas sensory and motor networks are considered more hardwired. "We all can see the rock falling and get out of the way," says cognitive neuroscientist Michael S. Gazzaniga of the University of California, Santa Barbara. "But some of us are better at figuring out why it fell in the first place."

The study authors do not support using these techniques to identify people. "We don't need to put people in a scanner to know who they are," Finn says. But the finding, published last fall in *Nature Neuroscience,* does suggest new clinical applications for fcMRI. "It could be a fingerprint for mental health," says neuroimaging expert Cameron Craddock of the Nathan S. Kline Institute for Psychiatric Research. Finn notes that her team has already started working with data from adolescents at high risk for schizophrenia to see if the scans can be used to predict who will go on to acquire the disorder. —*Simon Makin*

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That Craving for Dessert

Junk foods can muddle the brain's satiety-control mechanism, sending our appetites into hyperdrive

By Ferris Jabr

Matthew Brien has struggled with overeating for the past 20 years. At age 24, he stood at 5'10" and weighed a trim 135 pounds. Today the licensed massage therapist tips the scales at 230 pounds and finds it particularly difficult to resist bread, pasta, soda, cookies and ice cream—especially those dense pints stuffed with almonds and chocolate chunks. He has tried various weight-loss programs that limit food portions, but he can never keep it up for long. "It's almost subconscious," he says. "Dinner is done? Okay, I am going to have dessert. Maybe someone else can have just two scoops of ice cream, but I am going to have the whole damn [container]. I can't shut those feelings down."

Eating for the sake of pleasure, rather than survival, is nothing new. But only in the past several years have researchers come to understand deeply how certain foods—particularly fats and sweets—actually change brain chemistry in a way that drives some people to overconsume.

Scientists have a relatively new name for such cravings: hedonic hunger, a powerful desire for food in the absence of any need for it; the yearning we experience when our stomach is full but our brain is still ravenous. And a growing number of experts now argue that hedonic hunger is one of the primary contributors to surging obesity rates in developed countries worldwide, particularly in the U.S., where scrumptious desserts and mouthwatering junk foods are cheap and plentiful.

"Shifting the focus to pleasure" is a new approach to understanding hunger and weight gain, says Michael Lowe, a clinical psychologist at Drexel University who coined the term "hedonic hunger" in 2007. "A lot of overeating, maybe all of the eating people do beyond their energy needs, is based on consuming some of our most palatable foods. And I think this approach has already had an influence on obesity treatment." Determining whether an individual's obesity arises primarily from emotional cravings as opposed to an innate flaw in the body's ability to burn up calories, Lowe says, helps doctors choose the most appropriate medications and behavioral interventions for treatment.

ANATOMY OF APPETITE

TRADITIONALLY RESEARCHERS concerned with hunger and weight regulation have focused on so-called metabolic or homeostatic hunger, which is driven by physiological necessity and is most commonly identified with the rumblings of an empty stomach. When we start dipping into our stores of energy in the course of 24 hours or when we drop below our typical body weight, a complex network of hormones and neural pathways in the brain ramps up our feelings of hunger. When we eat our fill or put on excess pounds, the same hormonal system and brain circuits tend to stifle our appetite.

By the 1980s scientists had worked out the major hormones and neural connections responsible for metabolic hunger. They discovered that it is largely regulated by the hypothalamus, a region of the brain that contains nerve cells that both trigger the production of and are exquisitely sensitive to a suite of disparate hormones.

As with so many biological mechanisms, these chemical signals form an interlocking web of checks and balances. Whenever people eat more calories than they immediately need, some of the excess is stored in fat cells found throughout the body. Once these cells begin to grow in size, they start churning out higher levels of a hormone called leptin, which travels through the blood to the brain, telling the hypothalamus to send out yet another flurry of hormones that reduce appetite and increase cellular activity to burn off the extra calories—bringing everything back into balance.

Similarly, whenever cells in the stomach and intestine detect the presence of food, they secrete various hormones, such as cholecystokinin and peptide YY, which work to suppress hunger either by journeying to the hypothalamus or by acting directly on the vagus nerve, a long, meandering bundle of nerve cells that link the brain, heart and gut. In contrast, ghrelin, a hormone released from the stomach when it is empty and blood glucose (sugar) levels are low, has the opposite effect on the hypothalamus, stimulating hunger.

By the late 1990s, however, brain-imaging studies and experiments with rodents began to reveal a second biological pathway—one that underlies the process of eating for pleasure. Many of the same hormones that operate in metabolic hunger appear to be involved in this second pathway, but the end result is activation of a completely different brain region, known as

Illustration by Ashley Mackenzie

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the reward circuit. This intricate web of neural ribbons has mostly been studied in the context of addictive drugs and, more recently, compulsive behaviors such as pathological gambling.

It turns out that extremely sweet or fatty foods captivate the brain's reward circuit in much the same way that cocaine and gambling do. For much of our evolutionary past, such calorie-dense foods were rare treats that would have provided much needed sustenance, especially in dire times. Back then, gorging on sweets and fats whenever they were available was a matter of survival. In contemporary society—replete with inexpensive, high-calorie grub—this instinct works against us. "For most of our history the challenge for human beings was getting enough to eat to avoid starvation," Lowe says, "but for many of us the modern world has replaced that with a very different challenge: avoiding eating more than we need so we don't gain weight."

Research has shown that the brain begins responding to fatty and sugary foods even before they enter our mouth. Merely seeing a desirable item excites the reward circuit. As soon as such a dish touches the tongue, taste buds send signals to various regions of the brain, which in turn responds by spewing the neurochemical dopamine. The result is an intense feeling of pleasure. Frequently overeating highly palatable foods saturates the brain with so much dopamine that it eventually adapts by desensitizing itself, reducing the number of cellular receptors that recognize and respond to the neurochemical. Consequently, the brains of overeaters demand a lot more sugar and fat to reach the same threshold of pleasure as they once experienced with smaller amounts of the foods. These people may, in fact, continue to overeat as a way of recapturing or even maintaining a sense of well-being.

Emerging evidence indicates that some hunger hormones that usually act on the hypothalamus also influence the reward circuit. In a series of studies between 2007 and 2011, researchers at the University of Gothenburg in Sweden demonstrated that the release of ghrelin (the hunger hormone) by the stomach directly increases the release of dopamine in the brain's reward circuit. The researchers also found that drugs that prevent ghrelin from binding to neurons in the first place curtail overeating in people who are obese.

Under normal conditions, leptin and insulin (which become abundant once extra calories are consumed) suppress the release of dopamine and reduce the sense of pleasure as a meal continues. But recent rodent studies suggest that the brain stops responding to these hormones as the amount of fatty tissue in the body increases. Thus, continued eating keeps the brain awash in dopamine even as the threshold for pleasure keeps going up.

CURBING CRAVINGS

A KIND OF SURGERY that some obese people already undergo to manage their weight underscores ghrelin's importance in weight control and has provided some of the biological insights into why many of us eat far beyond our physiological needs. Known as bariatric surgery, it is a last-resort treatment that dramatically shrinks the stomach, either by removing tissue or by squeezing the organ so tightly with a band that it cannot accommodate more than a couple of ounces of food at a time.

Within a month after such surgery, patients are typically less hungry overall and are no longer as attracted to foods high in sugar and fat—possibly because of changes in the amount of hormones that their much smaller stomach can now produce. Recent brain-scanning studies reveal that these reduced cravings mirror changes in neural circuitry: postsurgery, the brain's reward circuit responds much more weakly to the images and spoken names of tempting foods, such as chocolate brownies, and becomes resensitized to smaller amounts of dopamine.

"The idea is that by changing the anatomy of the gut we are changing levels of gut hormones that eventually get to the brain," says Kimberley Steele, a surgeon at the Johns Hopkins University School of Medicine. A few studies have documented lower levels of hunger-stimulating ghrelin and increased levels of appetite-suppressing peptide YY following bariatric surgery. As recent experiments suggest, these hormones act not only on the hypothalamus but also on the reward circuit. "In the long term, we can probably mimic the effects of bariatric surgery with drugs," says Bernd Schultes of the eSwiss Medical & Surgical Center in St. Gallen, Switzerland. "That is the great dream."

In the meantime, several clinicians are using recent revelations about hedonic hunger to help people like Brien. Yi-Hao Yu, one of Brien's doctors at Greenwich Hospital in Connecticut, proposes that obesity takes at least two distinct but sometimes overlapping forms: metabolic and hedonic. Because he believes Brien struggles primarily with hedonic obesity, Yu recently prescribed the drug Victoza, which is known to reduce pleasure-driven eating. In contrast, drugs that typically target the hypothalamus would work better if a patient's underlying problem was a flaw in the body's ability to maintain a steady weight.

Drexel's Lowe, for his part, has focused on new approaches to behavior modification. "The traditional idea is that we can teach overweight people to improve their self-control," Lowe says. "The new idea is that the foods themselves are more the problem." For some people, palatable foods invoke such a strong response in the brain's reward circuit—and so dramatically alter their biology—that willpower will rarely, if ever, be sufficient to resist eating those foods once they are around. Instead, Lowe says, "we have to reengineer the food environment." In practical terms, that means never bringing fatty, supersweet foods into the house in the first place and avoiding venues that offer them whenever possible.

Elizabeth O'Donnell has put these lessons into practice. A 53-year-old store owner who lives in Wallingford, Pa., O'Donnell learned to modify her personal food environment at home and on the road after participating in one of Lowe's weight-loss studies. She says she is particularly helpless before sweets and pastries and so has committed to keeping them out of her home and to avoiding restaurants with all-you-can-eat dessert tables—which in the past led her to consume "an excess of 3,000 or 4,000 calories." On a recent visit to Walt Disney World, for example, she bypassed the park's many buffet-style restaurants in favor of a smaller, counter-service eatery, where she bought a salad. That's exactly the kind of simple change that can make a huge difference in the struggle to maintain a healthy weight. SA

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

Click 'n' Pay

There's a way to banish online ads. If we pony up

By David Pogue

On the Internet, ads are a real problem.

They're a problem for us, the people, and not just because they clutter up our Web pages; they also cost us money (in mobile data charges), battery life and time. As much as 79 percent of the time it takes for a news Web site to load on your phone is waiting for the ads to arrive, according to a *New York Times* analysis.

Surprisingly, they're also a problem for advertisers and Web sites. Suddenly the popularity of ad-blocking software has reached a tipping point. According to a study by Adobe and PageFair (which offers *anti*-ad-blocking services), 41 percent of adults younger than 30 use these blockers. Overall, ad-blocker installations are up 48 percent in a year—and that was before Apple began approving ad-blocking apps for the iPhone and iPad last September, marking the first time ad blocking has come to the mobile world in a huge way.

The thing is, most of those free articles, videos and services you enjoy are brought to you by the advertising. If you're not seeing the ads, then the central financial transaction of the online content economy collapses. What then?

Some Web sites appeal to visitors directly, asking you to view the ads. Last summer Wired.com's home page said, "Please do us a solid and disable your ad blocker."

Other sites simply turn you away if you have an ad blocker installed. The sites for leading U.K. broadcasters Channel 4 and ITV present a dark screen and a simple declaration to the effect of: "We are now preventing ad-blocked access."

Enter ad-blocker-*blocking* technology—Web software that tries to fool the ad blockers so that the ads appear despite your blocker. Some companies that operate ad blockers even accept money from large advertisers, although they deny giving ads from those companies special treatment.

But these tactics treat the public as the enemy. They create a technology arms race. "You *will* see our ads, like it or not!"

Advertising executives may tell you, upon rising from yet another sleepless night, that one solution may be native advertising: ads dressed up as articles. Although they represent the advertiser's interests, they're displayed as actual stories or videos rather than splashy ads, so they pass through ad blockers. These can lead to some murky territory, however, blurring the line between traditional content and that aiming to sell you something.

So tech utopians like me wonder why the answer isn't micropayments. You know, instead of looking at ads, you're automatically billed a few cents for each article you read or video you watch. In our hearts, we know that *somebody* has to pay for all that Web goodness. If the micropayments were cheap and easy, couldn't they make all parties happy?

Unfortunately, we've already tried that. In the late 1990s and early 2000s a bunch of companies tried to invent micropayment systems; all of them failed.

To find out why, I tracked down the CEOs of some of the start-ups, who have all moved on to other endeavors.

"Micropayments sound great on paper," former BitPass CEO Douglas Knopper told me. "But in practice, they require four things for the consumer that are hard to pull off: simplicity, ubiquity, security—and it has to be free. The economics to the retailer don't work, because there are too many middlemen—credit-card processors, etc. So until someone figures out how to crack the code … micropayments aren't going to get any traction."

The timing was wrong, too. Charles Cohen, founder of failed micropayment company Beenz, told me that these efforts mostly died "because the dot-com bubble burst, and most of the companies who were accepting and issuing our microcurrency went up in a puff of smoke."

So micropayments may face an uphill battle, but there aren't any screamingly obvious reasons why they couldn't work now. It seems Web companies would be happy to get out of the ad-blocking arms race, while Web users, well, we wouldn't mind paying a few cents here and there to never encounter another intrusive banner ad or slow-to-load video ad. As Kurt Huang, co-founder of BitPass (R.I.P.), puts it, "Micropayments could indeed make a comeback."

On behalf of millions of Web sites, advertisers and readers, I'd love for him to be right. SA

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WHO WILL SAVE THE ONLINE CONTENT ECONOMY?: ScientificAmerican.com/Jan2016/pogue

Illustration by Dan Schlitzkus

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NEUROSCIENCE

WHERE AM I? WHERE AM I GOING?

Scientists are discovering how the brain navigates

By May-Britt Moser and Edvard I. Moser

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Illustration by Viktor Koen

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May-Britt Moser and **Edvard I. Moser** are professors in psychology and neuroscience at the Norwegian University of Science and Technology in Trondheim. The two co-founded the Kavli Institute for Systems Neuroscience in 2007 and the Center for Neural Computation in 2013, both located at the university. In 2014 they shared the Nobel Prize in Physiology or Medicine with John O'Keefe of University College London for the discovery of the brain's positioning system.

Our ability to pilot a car or airplane—or even to walk through city streets—has been completely transformed by the invention of the Global Positioning System (GPS). How did we navigate, though, before we had GPS? Recent work has shown that the mammalian brain uses an incredibly sophisticated GPS-like tracking system of its own to guide us from one location to the next.

Like the GPS in our phones and cars, our brain's system assesses where we are and where we are heading by integrating multiple signals relating to our position and the passage of time. The brain normally makes these calculations with minimal effort, so we are barely conscious of them. It is only when we get lost or when our navigation skills are compromised by injury or a neurodegenerative disease that we get a glimpse of how critical this mapping-and-navigation system is to our existence.

The ability to figure out where we are and where we need to go is key to survival. Without it, we, like all animals, would be unable to find food or reproduce. Individuals—and, in fact, the entire species—would perish.

The sophistication of the mammalian system becomes particularly clear when contrasted to those of other animals. The simple roundworm *Caenorhabditis elegans,* which has just 302 neurons, navigates almost solely in response to olfactory signals, following the path of an increasing or decreasing odor gradient.

Animals with more sophisticated nervous systems, such as desert ants or honeybees, find their way with the help of additional strategies. One of these methods is called path integration, a GPS-like mechanism in which neurons calculate position based on constant monitoring of the animal's direction and speed of movement relative to a starting point—a task carried out without reference to external cues such as physical landmarks. In vertebrates, particularly in mammals, the repertoire of behaviors that enable an animal to locate itself in its environment has expanded still further.

More than any other class of animals, mammals rely on the capacity to form neural maps of the environment—patterns of electrical activity in the brain in which groups of nerve cells fire in a way that reflects the layout of the surrounding environment and an animal's position in it. The formation of such mental maps is mostly thought to occur in the cortex, the brain's wrinkled upper layers that developed quite late in evolution.

Over the past few decades researchers have gained a deep understanding of just how the brain forms and then revises

IN BRIEF

Determining where we are in relation to our surroundings—streets, trees or other landmarks around us—remains an essential skill without which our own survival, or even that of our species, would rapidly be endangered.

Networks of cells lodged deep within the brain work together to assemble an internal mental map of our environment that enables us to find our way seamlessly from place to place, as if these cells equated to a biological Global Positioning System.

Regions of the brain involved with pathfinding are also intimately connected to the formation of new memories. When these neural tracts malfunction, they can produce the severe disorientation experienced by a patient with Alzheimer's disease.

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these maps as an animal moves. The recent work, conducted mostly in rodents, has revealed that the navigation systems consist of several specialized cell types that continuously calculate an animal's location, the distance it has traveled, the direction it is moving and its speed. Collectively these different cells form a dynamic map of local space that not only operates in the present but also can be stored as a memory for later use.

A NEUROSCIENCE OF SPACE

THE STUDY of the brain's spatial maps began with Edward C. Tolman, a psychology professor at the University of California, Berkeley, from 1918 to 1954. Before Tolman's work, laboratory experiments in rats seemed to suggest that animals find their way around by responding to—and memorizing—successive stimuli along the path they move. In learning to run a maze, for instance, they were thought to recall sequences of turns they made from the maze's start to its end. This idea, however, did not take into account that the animals might visualize an overall picture of the entire maze to be able to plan the best route.

Tolman broke radically with prevailing views. He had observed rats take shortcuts or make detours, behaviors that would not be expected if they had learned only one long sequence of behaviors. Based on his observations, he proposed that animals form mental maps of the environment that mirror the spatial geometry of the outer world. These cognitive maps did more than help animals to find their way; they also appeared to record information about the events that the animals experienced at specific locales.

Tolman's ideas, proposed for the first time around 1930, remained controversial for decades. Acceptance came slowly, in part because they were based entirely on observing the behavior of experimental animals, which could be interpreted in many ways. Tolman did not have the concepts or tools to test whether an internal map of the environment actually existed in an animal's brain.

It took about 40 years before direct evidence for such a map appeared in studies of neural activity. In the 1950s progress in the development of microelectrodes made it possible to monitor electrical activity from individual neurons in awake animals. These very thin electrodes enabled researchers to identify the firing of single neurons as the animals went about their business. A cell "fires" when it triggers an action potential—a short-lasting change in the voltage across the neuronal cell membrane. Action potentials cause neurons to release neurotransmitter molecules that convey signals from one neuron to another.

John O'Keefe of University College London used microelectrodes to monitor action potentials in rats in the hippocampus, an area of the brain known for decades to be important for memory functions. In 1971 he reported that neurons there fired when a rat in a box spent time at a certain location—thus, he called them place cells. O'Keefe observed that different place cells fired at different locations in the box and that the firing pattern of the cells collectively formed a map of locations in the box. The combined activity of multiple place cells could be read out from the electrodes to identify the animal's precise location at any given time. In 1978 O'Keefe and his colleague Lynn Nadel, now at the University of Arizona, suggested that place cells were, in fact, an integral part of the cognitive map Tolman had envisaged.

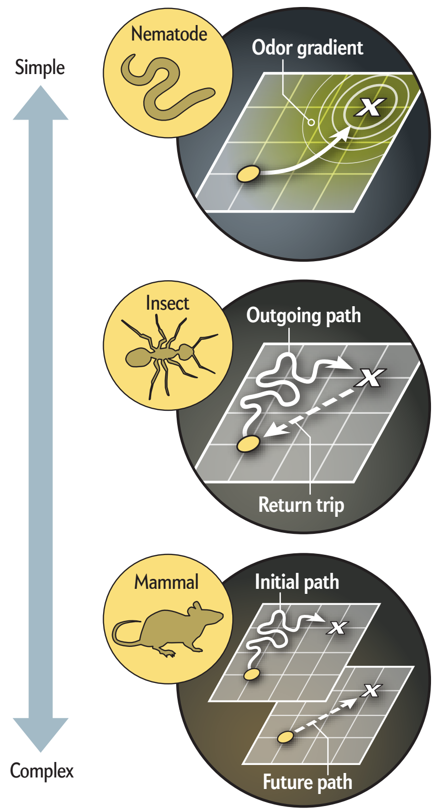
A CORTICAL MAP

THE DISCOVERY of place cells opened a window into the deepest parts of the cortex, in areas farthest away from the sensory cor-

NATURE'S NAVIGATORS

The Nervous System's Incredible Pathfinding Skills

Survival for any species requires an ability to take into account the surrounding environment and to make a calculation, even a crude one, of where an animal has been, where it is and where it is going. On higher rungs of the evolutionary chain, many species have developed "path integration" systems that allow them to perform this task without the need to locate where they are by referencing external landmarks. Mammals have found an even more elaborate solution that uses internalized mental maps.



Tracing a Smell
The simple roundworm *Caenorhabditis elegans* exhibits perhaps the most basic animal navigation system. The worm world is organized according to smell. Equipped with a mere 302 neurons, it pushes itself straight ahead toward a food source by sensing ever increasing levels of an odor.

Internal GPS
Evolution has equipped even some insects and other arthropods with elaborate path-integration capabilities. They can monitor internally their speed and direction relative to a starting point. This allows them to find more efficient means of traveling a given route—a direct return instead of the zigs and zags traversed on an outbound journey.

Mental Maps
Mammals have evolved still more intricate orienteering skills in which neurons fire in their brain in sequences that mirror the routes they travel. These networks of neurons make up mental maps of the physical world. Animals store memories of past journeys and use them for the planning of future trips.

Illustrations by Jen Christiansen

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tices (those that receive inputs from the senses) and from the motor cortex (which emits the signals that initiate or control movement). At the end of the 1960s, when O'Keefe started his work, knowledge about when neurons switched on and off was largely restricted to areas called the primary sensory cortices, where neural activity was controlled directly by such sensory inputs as light, sound and touch.

Neuroscientists of that era speculated that the hippocampus was too far removed from the sensory organs to process their inputs in any manner that could easily be understood from a microelectrode recording. The discovery of cells in the hippocampus that created a map of an animal's immediate environment dashed that speculation.

Even though the finding was remarkable and suggested a role for place cells in navigation, no one knew what that role might be for decades after their discovery. Place cells were in an area of the hippocampus, called CA1, that was the end point in a signaling chain originating elsewhere in the hippocampus. It was hypothesized that place cells received many of the critical navigation-related computations from other hippocampal regions. In the early 2000s the two of us decided to explore this idea further in the new lab we had set up at the Norwegian University of Science and Technology in Trondheim. This pursuit ultimately led to a major discovery.

In collaboration with Menno Witter, now at our institute, and a set of highly creative students, we began by using microelectrodes to monitor the activity of place cells in the rat hippocampus after we had disrupted part of a neuronal circuit there known to feed information to these cells. We expected the work to confirm that this circuit was important to the proper functioning of the place cells. To our surprise, the neurons at the end of that circuit, in CA1, still fired when the animals arrived at specific locations.

Our team's inescapable conclusion was that place cells did not depend on this hippocampal circuit to gauge an animal's bearings. Our attention then turned to the only neural pathway that had been spared by our intervention: the direct connections to CA1 from the entorhinal cortex, an adjoining area that provides an interface to the rest of the cortex.

In 2002 we inserted microelectrodes in the entorhinal cortex, still in a collaboration with Witter, and began recording as the animals performed tasks that were similar to the ones we had used for our place cell studies. We guided electrodes into an area of the entorhinal cortex having direct connections to the parts of hippocampus where place cells had been recorded in almost every study before ours. Many cells in the entorhinal cortex turned out to fire when an animal was at a particular spot in the enclosure, much like the place cells in the hippocampus do. But unlike a place cell, a single cell in the entorhinal cortex fired, not only at one location visited by a rodent but at many.

The most striking property of these cells, though, was the way they fired. Their pattern of activity became obvious to us only when, in 2005, we increased the size of the enclosure in which we were recording. After expanding it to a certain size, we found that the multiple locations at which an entorhinal cell fired formed the vertices of a hexagon. At each vertex, the cell, which we called a grid cell, fired when the animal passed over it.

The hexagons, which covered the entire enclosure, appeared to form the individual units of a grid—similar to the squares formed by the coordinate lines on a road map. The firing pattern raised the possibility that grid cells, unlike place cells, provide information about distance and direction, helping an animal to track its trajectory based on internal cues from the body's motions without relying on inputs from the environment.

Several aspects of the grid also changed as we examined the activity of cells in different parts of the entorhinal cortex. At the dorsal part, near the top of this structure, the cells generated a grid of the enclosure that consisted of tightly spaced hexagons. The size of the hexagons increased in a series of steps—or modules—as one moved toward the lower, or ventral, part of the entorhinal cortex. The hexagonal grid elements in each module had a unique spacing.

The spacing of the grid cells in each successive module moving downward could be determined by multiplying the distance between cells in the previous module by a factor of about 1.4, approximately the square root of 2. In the module at the top of the entorhinal cortex, a rat that activated a grid cell at one vertex of a hexagon would have to travel 30 to 35 centimeters to an adjoining vertex. In the next module down, the animal would have to travel 42 to 49 centimeters, and so on. In the lowest module, the distance extended up to several meters in length.

We were extremely excited by the grid cells and their tidy organization. In most parts of the cortex, the neurons have firing patterns that appear chaotic and inaccessible, but here, deep in the cortex, there was a system of cells that fired in a predictable and orderly pattern. We were eager to investigate. But these cells and place cells were not the only ones involved in mapping the mammal's world—other surprises also awaited us.

Humans and other mammals form internal maps of the environment—patterns of neural activity in which brain cells fire to reflect where an animal is and where it is positioned in relation to its surroundings.

Back in the mid-1980s and early 1990s, James B. Ranck of SUNY Downstate Medical Center and Jeffrey S. Taube, now at Dartmouth College, had described cells that fired when a rodent faced a particular direction. Ranck and Taube had discovered such head-direction cells in the presubiculum, another region of the cortex adjacent to the hippocampus.

Our studies found that these cells were also present in the entorhinal cortex, intermingled among grid cells. Many head-direction cells in the entorhinal cortex also functioned as grid cells: the locations in the enclosure where they fired also formed a grid, but the cells became active at those locales only when the rat was facing a certain direction. These cells appeared to provide a compass for the animal; by monitoring the cells, one

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could read out the direction the animal was facing at any given time relative to the surrounding environment.

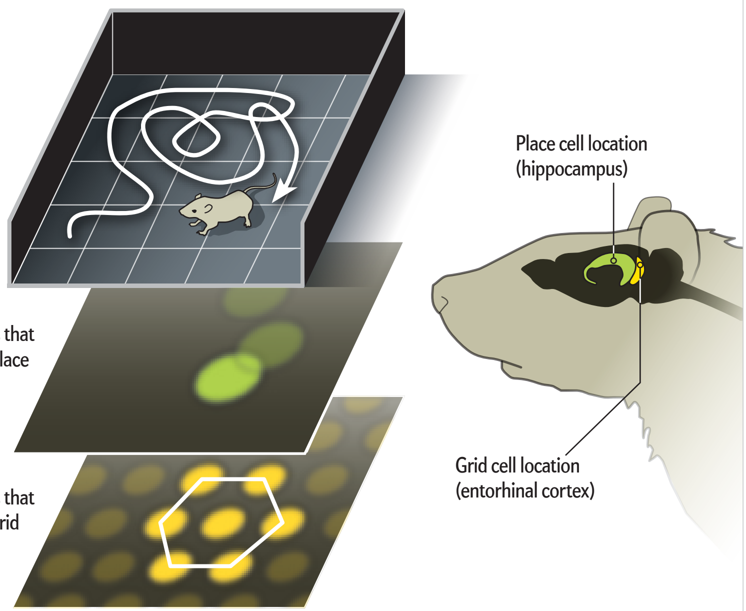
A few years later, in 2008, we made a discovery in the entorhinal cortex of another cell type. These border cells fired whenever the animal approached a wall or an edge of the enclosure or some other divide. These cells appeared to calculate how far the animal was from a boundary. This information could then be used by grid cells to estimate how far the animal had traveled from the wall, and it could also be established as a reference point to remind the rat of the wall's whereabouts at a later time.

Finally, in 2015, yet a fourth kind of cell entered the scene. It responded specifically to the running speed, regardless of the animal's location or direction. The firing rates of these neurons increased in proportion to the speed of movement. Indeed, we could ascertain how fast an animal was moving at a given moment by looking at the firing rates of just a handful of speed cells. In conjunction with head-direction cells, speed cells may serve the role of providing grid cells continually updated information about the animal's movement—its speed, direction and the distance from where it started.

NEUROCARTOGRAPHY

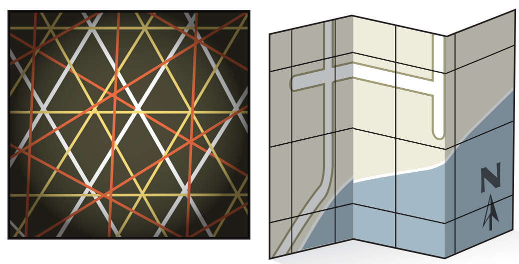
How the Brain Takes Its Bearings

The idea that the brains of mammals make a mental map that mirrors the spatial geometry of the outer world first emerged around 1930. Neuroscientists have subsequently identified cells that work together to create such maps. A key development came in 1971, when an American-British researcher found that place cells in the rat hippocampus fire at particular locations on the willy-nilly path an animal travels. In 2005 the authors discovered grid cells that let an animal measure its location in its environment—say, in relation to the walls of an enclosure. As the animal moves about, each grid cell fires at multiple locations that correspond to the vertices of a hexagon.



A Cognitive Map Emerges

Firing of grid cells produces a map (*right*), akin to a geographical map (*far right*). Together with place cells that identify the animal's location in a particular environment, grid cells enable the animal to build a mental picture of its surroundings.



SOURCE: "SCIENTIFIC BACKGROUND: THE BRAIN'S NAVIGATIONAL PLACE AND GRID CELL SYSTEM," BY OLE KIEHN AND HANS FORSSBERG, WITH ILLUSTRATIONS BY MATTIAS KARLEN. NOBELPRIZE.ORG, NOBEL MEDIA AB, 2014 *www.nobelprize.org/nobel_prizes/medicine/laureates/2014/advanced.html (top)*

FROM GRID TO PLACE CELLS

Our discovery of grid cells grew out of our desire to uncover the inputs that allow place cells to give mammals an internal picture of their environment. We now understand that place cells integrate the signals from various types of cells in the entorhinal cortex as the brain attempts to track the route an animal has traveled and where it is going in its environment. Yet even these processes do not tell the whole story of how mammals navigate.

Our initial work focused on the medial (inner) entorhinal cortex. Place cells may also receive signals from the lateral entorhinal cortex, which relays processed input from a number of sensory systems, including information about odor and identity of objects. By integrating inputs from the medial and lateral parts of the entorhinal cortex, place cells interpret signals from throughout the brain. The complex interaction of messages arriving in the hippocampus and the formation of location-specific memories that this enables are still being investigated by our lab and others, and this research will undoubtedly continue for many years to come.

One way to begin to understand how the spatial maps of the medial entorhinal cortex and the hippocampus combine to aid navigation is to ask how the maps differ. John Kubie and the late Robert U. Muller, both at SUNY Downstate Medical Center, showed in the 1980s that maps in the hippocampus made up of place cells may change entirely when an animal moves to a new environment—even to a different colored enclosure at the same location in the same room.

Experiments performed in our own lab, with rats foraging in up to 11 enclosures in a series of different rooms, have shown that each room, in fact, rapidly gives rise to its own independent map, further supporting the idea that the hippocampus forms spatial maps tailored to specific environments.

In contrast, the maps in the medial entorhinal cortex are universal. Grid cells—and head-direction and border cells—that fire together at a particular set of locations on the grid map for one environment also fire at analogous positions on the map for another

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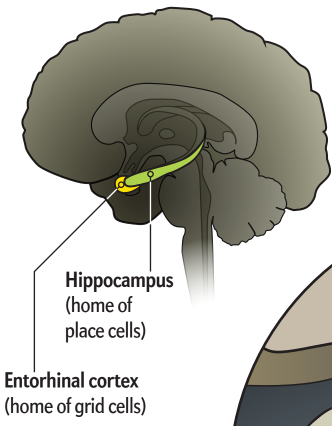
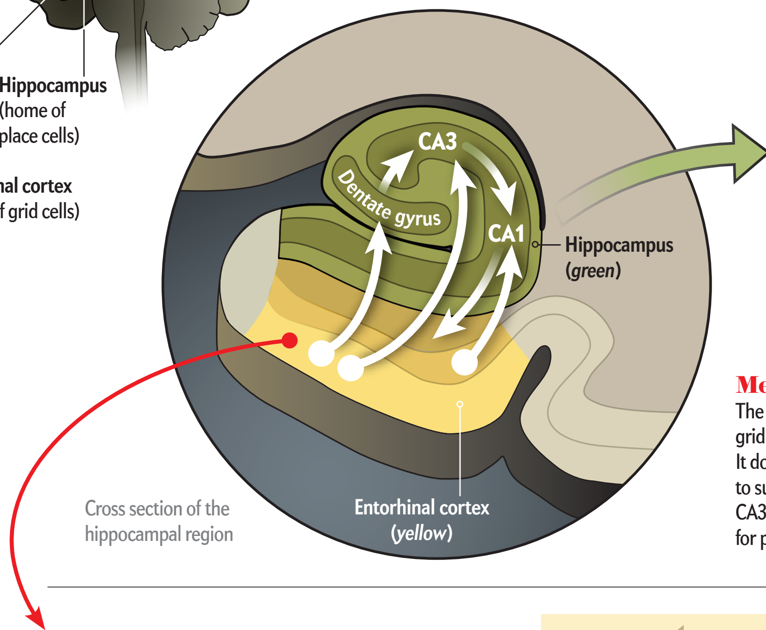
A PARTS LIST

Inside the Brain's GPS

The neural navigation system of the human brain resides deep within a region known as the medial temporal lobe. Two areas of the medial temporal lobe—the entorhinal cortex and the hippocampus—act as key components of the brain's GPS. Networks of specialized cell types in the entorhinal cortex contribute to the complexity in the mammalian brain's pathfinding system.



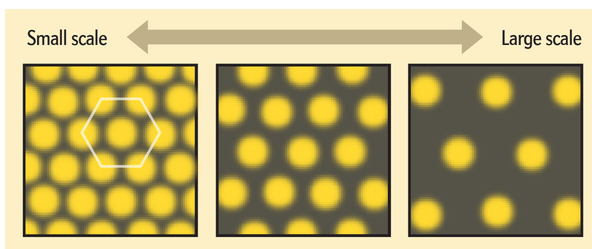


Messaging the Hippocampus

The entorhinal cortex transmits information from grid cells about direction and distance traveled. It does so by sending signals along several pathways to subregions of the hippocampus (the dentate gyrus, CA3 and CA1) that produce a mental map optimized for planning future journeys (*inset*).

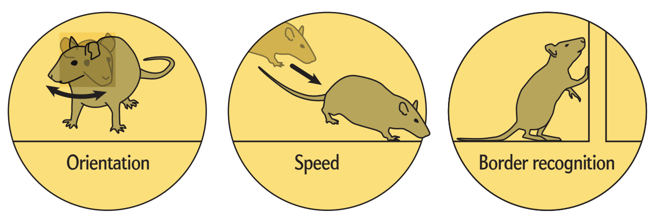
A Close Look at Grid Cell Organization …

… reveals that the spacing of the hexagonal elements that aid in creating a spatial map change when moving from top to bottom in the entorhinal cortex. The broader spacings correspond to larger distances the rat needs to travel to activate a vertex on the grid. At the top of the entorhinal cortex, a rat that activates a grid cell at one vertex of a hexagon will have to move 30 to 35 centimeters to an adjoining vertex. At the bottom, the animal needs to go as far as several meters.



Other Specialized Cells Recently Discovered …

… in the entorhinal cortex of rodents convey information to the hippocampus about the orientation of an individual's head, its speed of movement, and the distance to walls and other obstacles encountered. The output of these cells is combined to help create a composite map of the animal's environs.



environment—as if latitude and longitude lines from the first map were imposed on the new setting. The sequence of cells that fire as the animal moves northeast in one room of the cage repeats when the rat goes in that same direction in the other room. The pattern of signaling among these cells in the entorhinal cortex is what the brain uses for navigating through its surroundings.

These codes are then transmitted from the entorhinal cortex to the hippocampus, where they are used to form maps specific to a particular place. From the standpoint of evolution, two sets of maps that integrate their information to guide animals appear to be an efficient solution for a system used by animals for spatial navigation. The grids formed in the medial entorhinal cortex that measure distance and direction do not change from one room to the next. In contrast, the place cells of the hippocampus form individual maps for every single room.

LOCAL MAPS

UNDERSTANDING of the neural navigation system remains a work in progress. Almost all our knowledge of place and grid cells has been obtained in experiments in which electrical activity

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from neurons is recorded when rats or mice walk about randomly in highly artificial environments—boxes with flat bottoms and no internal structures to serve as landmarks.

A lab differs substantially from natural environments, which change constantly and are full of three-dimensional objects. The reductionism of the studies raises questions about whether place cells and grid cells fire in the same way when animals find themselves outside the lab.

Experiments in complex mazes that try to mimic animals' natural habitat provide a few clues to what might be going on. In 2009 we recorded grid cells as animals moved through an intricate maze in which they encountered a hairpin turn at the end of each alley that marked the beginning of the next passageway. The study showed that, as expected, grid cells formed patterns of hexagons to map out distances for the rats in individual alleys of the maze. But each time an animal turned from one alley to the next, an abrupt transition occurred. A separate grid pattern was then superimposed on the new alley, almost as if the rat were entering an entirely different room.

Later work in our lab has shown that grid maps also fragment into smaller maps in open environments if these spaces are large enough. We are now researching how these smaller maps merge to form an integrated map of a given area. Even these experiments are oversimplified because the enclosures are flat and horizontal. Experiments performed in other labs—observing flying bats and rats that climb around in cages—are beginning to provide some clues: place cells and head-direction cells seem to fire in specific places throughout any three-dimensional space, and most likely grid cells do as well.

SPACE AND MEMORY

THE NAVIGATIONAL SYSTEM in the hippocampus does more than help animals get from point A to point B. Beyond receiving information about position, distance and direction from the medial entorhinal cortex, the hippocampus makes a record of what is located in a particular place—whether a car or a flagpole—as well as the events that take place there. The map of space created by place cells thus contains not only information about an animal's whereabouts but also details about the animal's experiences, similar to Tolman's conception of a cognitive map.

Some of this added information appears to come from neurons in the lateral part of the entorhinal cortex. Particulars about objects and events fuse with an animal's coordinates and are laid down as a memory. When the memory is later retrieved, both the event and the position are called to mind.

This coupling of place with memory recalls a strategy for memorization invented by ancient Greeks and Romans. The "method of loci" lets a person memorize a list of items by imagining putting each item at a position along a well-known path through a place, say, a landscape or a building—an arrangement often called a memory palace. Participants in memory contests still use the technique to recall long lists of numbers, letters or playing cards.

Sadly, the entorhinal cortex is among the first areas to fail in people with Alzheimer's disease. The illness causes brain cells there to die, and a reduction in its size is considered a reliable measure for identifying at-risk individuals. The tendency to wander and get lost is also among the earliest indicators of the disorder. In the later stages of Alzheimer's, cells die in the hippocampus, producing an inability to recall experiences or remember concepts such as the names of colors. In fact, a recent study has provided evidence that young individuals with a gene that places them at an elevated risk for Alzheimer's may have deficiencies in the functioning of their grid cell networks—a finding that may lead to new ways of diagnosing the disease.

A RICH REPERTOIRE

TODAY, MORE THAN 80 YEARS since Tolman first proposed the existence of a mental map of our surroundings, it is clear that place cells are just one component of an intricate representation the brain makes of its spatial environment to calculate location, distance, speed and direction. The multiple cell types that have been found in the navigation system of the rodent brain also occur in bats, monkeys and humans. Their existence across mammalian taxonomic orders suggests that grid and other cells involved in navigation arose early in the evolution of mammals and that similar neural algorithms are used to compute position across species.

Many of the building blocks of Tolman's map have been discovered, and we are beginning to understand how the brain creates and deploys them. The spatial representation system has become one of the best-understood circuits of the mammalian cortex, and the algorithms it uses are beginning to be identified to help unlock the neural codes the brain uses for navigation.

As with so many other areas of inquiry, new findings raise new questions. We know that the brain has an internal map, but we still need a better understanding of how the elements of the map work together to produce a cohesive representation of positioning and how the information is read by other brain systems to make decisions about where to go and how to get there.

Other questions abound. Is the spatial network of the hippocampus and the entorhinal cortex limited to navigation of local space? In rodents, we examine areas that have radii of only a few meters. Are place and grid cells also used for long-distance navigation, such as when bats migrate hundreds or thousands of kilometers?

Finally, we wonder how grid cells originate, whether there is a critical formative period for them in an animal's development and whether place and grid cells can be found in other vertebrates or invertebrates. If invertebrates use them, the finding would imply that evolution has used this spatial-mapping system for hundreds of millions of years. The brain's GPS will continue to provide a rich trove of leads for new research that will occupy generations of scientists in the decades ahead. SA

MORE TO EXPLORE

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FROM OUR ARCHIVES

The Matrix in Your Head. James J. Knierim; *Scientific American Mind,* June/July 2007.

scientificamerican.com/magazine/sa

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MORE THAN 400 LIGHT-YEARS away from Earth, the 16-million-year-old star J1407 (*upper left*) harbors a giant world wreathed by the largest planetary ring system ever seen. Nestled within a gap inthe planet's rings, a newborn Mars-sized moon (*foreground*) still glows from the heat of its formation.

Illustration by Ron Miller

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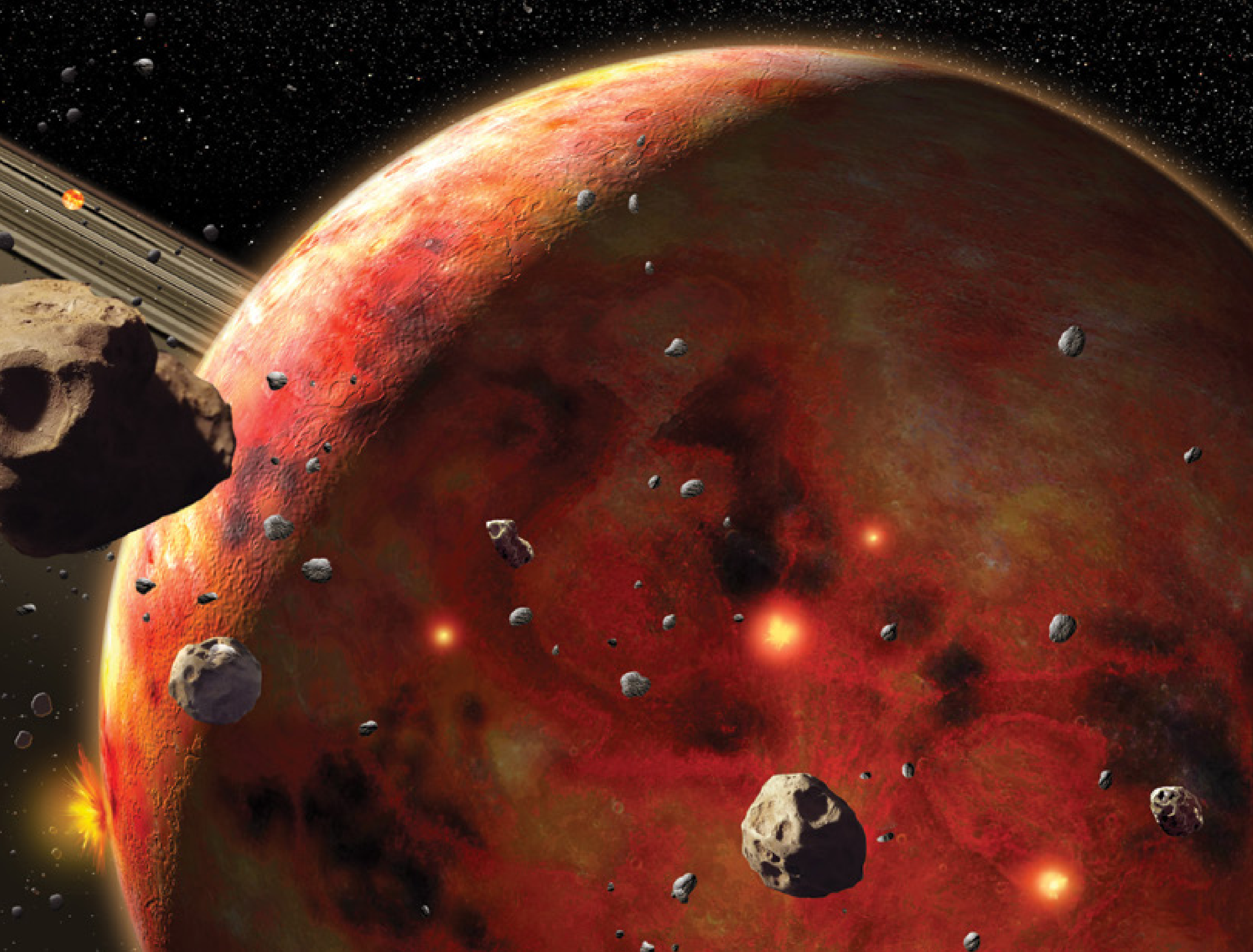
PLANETARY SCIENCE

Rings of a Super Saturn

Astronomers have discovered a gargantuan planetary ring system and possibly a moon around another star

By Matthew Kenworthy



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Matthew Kenworthy is an associate professor of astronomy at Leiden Observatory in the Netherlands. He studies planets around other stars and produces optical coronagraphs to help take pictures of them. In his spare time, he makes bread and cycles with his family around the Dutch countryside.

MUCH ASTRONOMY TAKES PLACE IN THE OFFICES AND OBSERVATORIES WHERE scientists work. But if you want to find the most exciting theories, you need to go where guards are lowered and wilder ideas can roam free.

It is not by coincidence that one of the best bars in Tucson, Ariz. (called 1702, after its street address), nestles close to Steward Observatory at the University of Arizona. It was there that my colleague Eric Mamajek of the University of Rochester showed me something that sent us on a quest to find the first ringed planet beyond our solar system, a quest involving both the world's most modern telescopes and century-old astronomical observations. Along the way, we found not only a ring system larger than Saturn's but also what seems to be a newborn moon.

SPOTTING THE RINGS

THE STORY BEGINS in 2011, when Mamajek and his then graduate student Mark Pecaut at Rochester were assembling a catalog of very young stars near to Earth. To guess the ages of their candidates, Mamajek and Pecaut checked the stars' rotation rates. Younger stars spin faster than older ones, and their spins can be clocked by watching for star spots (darker, cooler regions on a star's surface) coming in and out of view.

One candidate for inclusion in the survey had no name, just a code based on the instruments that observed it and its position in the sky, in the constellation of Centaurus: 1SWASP J140747.93-394542.6. We now call it J1407 for short. It and the other stars under consideration were too far away for their spots to be seen directly, so Mamajek and Pecaut instead examined J1407's "light curve"—a plot of its brightness over time—looking for small dips when spots spun into view and reduced the starlight. Planets can also cause such dips when they "transit" across their stars as seen from Earth. Mamajek and Pecaut found J1407's curve in the database of a planet-hunting camera survey called SuperWASP, which to date has found more than 100 transiting planets by monitoring about 31 million stars.

The light curve did suggest that J1407 was a young, rapidly spinning star, but it also held other, more intriguing information. A casual glance at SuperWASP's light curve for J1407 showed that in 2007 the otherwise unremarkable star flickered in an unpredictable pattern for many nights, then repeatedly dimmed to near invisibility over a week, before finally returning to its usual brightness. Data from other years showed no such variability in the star. In 2007 the odd event did not make much of an impression, and the curve had then languished unnoticed in the archives. But after he saw it in 2011, Mamajek could not forget about it.

"I put a printout of the light curve on my office wall, and I looked at it for weeks," he recalled to me in the bar in Tucson. "The crazy structure and detail were unique. What could cause these rapid changes in the star's brightness?"

IN BRIEF

Researchers have discovered a ring system some 200 times larger than Saturn's around a giant planet orbiting a distant star in the Milky Way.

Using state-of-the-art observations and archival data, professional and amateur astronomers are joining forces to study the system in more detail.

Models of the rings suggest they harbor a Mars-sized moon. If confirmed, this moon would be the first detected beyond our solar system, suggesting more await discovery. Further studies of this unique system promise to reveal new, unprecedented details of how planets and moons form around other stars.

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Soon after that discussion we began working together to solve the mystery. We quickly ruled out such obvious culprits as problems with the SuperWASP cameras or poor observing conditions. Whatever it was, the source of J1407's mysterious dimming was not located on Earth.

We soon concluded that something very fast and very big must be eclipsing J1407 and making it flicker. The speed of the brightness fluctuations suggested that the eclipsing object was racing in front of the star's face at 30 kilometers per second, and yet the eclipse itself lasted for 56 days! This long duration meant that the object was some 180 million kilometers in size.

There are only so many plausible explanations for what a structure so large could be. One by one, we considered and then dismissed them. Could it be a belt of dust orbiting close to the star? No, there was no telltale infrared glow around J1407 that you would expect from warm dust. Was this a binary system, with a giant red star eclipsing a smaller companion such as a white dwarf, neutron star or black hole? No, such systems tend to emit far more x-rays than we were seeing, and J1407 did not appear to be a giant star. Could the flickering be a coincidence caused by the shadow of something floating in deep interstellar space between Earth and the star, or could J1407 perhaps be a complex triple-star system, with an eclipsing 180-million-kilometer wide companion? No, neither of those possibilities matched the data, either. In the end, the simplest explanation consistent with all the observations was also something very strange: the dips in the light curve could be caused by a giant ring system some 200 times larger than Saturn's, orbiting an unseen planet that had passed between J1407 and Earth in 2007.

But why did we think it was a ring system? The most striking feature in the light curve was the level of detail that could be seen at all timescales—the eclipses lasted 56 days, but rapid changes could be seen to happen in as little as 20 minutes. These speeds hinted that the giant eclipsing object had large amounts of substructure, and the roughly symmetric shape of the light curve suggested that the object possessed a circular or elliptical geometry—much like the familiar ring system of Saturn. If we were right, the gargantuan planetary rings would be the first found outside our own solar system.

PLANET HUNTING

IF THIS TRULY was a giant ring system, then there had to be a giant planet around J1407 to bind the rings in place. So we went looking for the planet, which we call J1407b, using advanced instrumentation on two of the largest observatories on Earth: the 10-meter Keck II telescope in Hawaii and the 8.2-meter Very Large Telescope in Chile.

Even the biggest, brightest planets are far fainter and more difficult to see than their host stars. But J1407 is very young for a star. Given its estimated age—only 16 million years—any gas-giant planet around it would still be glowing brightly in infrared light from the heat of its formation. Based on J1407's distance from us, its predicted companion, when seen through a powerful telescope, would appear to be separated from the star by only about 50 milliarcseconds—equivalent to the distance between the goalposts of a football field seen on the surface of the moon. Though challenging, the observation was just within the realm of possibility.

For two years we sought to image the planet while looking for telltale periodic shifts in the star's motion caused by the to-

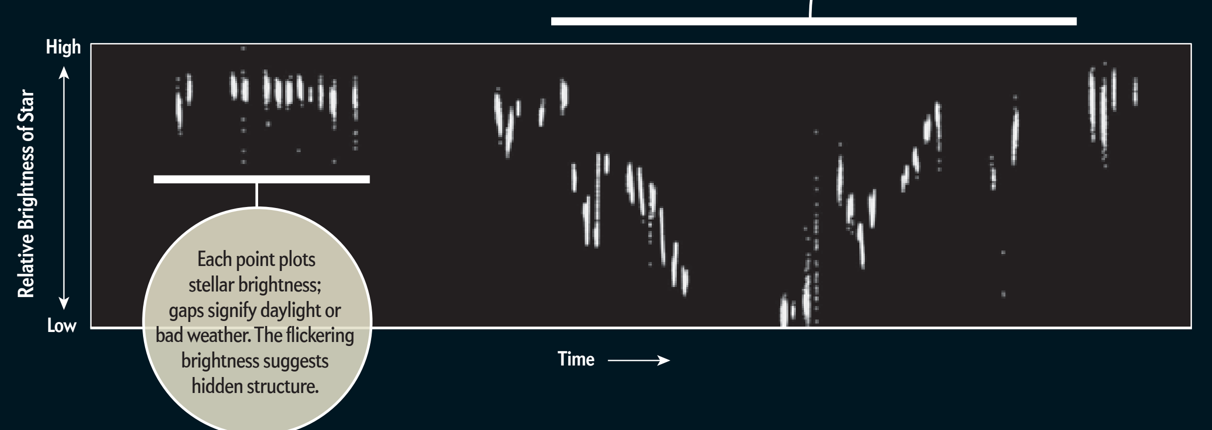
A MYSTERY OF LIGHT AND SHADOW

Perplexing Pattern

A light curve—an object's variance in brightness plotted over time—is a basic tool for studying stars. A brief boost in brightness can be caused by stellar flares, whereas momentary dips can signal star spots or the shadow of an orbiting planet. But the wildly fluctuating light curve of the star J1407 in 2007 (*below*) was unlike anything astronomers had ever seen. Something strange was making the star flicker and fade for months at a time.

Between two periods of flickering, J1407's light dimmed for 56 days, suggesting the star was eclipsed by an object 180 million kilometers wide.

J1407'S ODD LIGHT CURVE, DURING A 2007 ECLIPSE



SOURCE: "ANALYSIS OF 1SWASP J140747.93–394542.6 ECLIPSE FINE-STRUCTURE: HINTS OF EXOMOONS," BY T.I.M. VAN WERKHOVEN, M. A. KENWORTHY AND E. E. MAMAJEK, IN *MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY*, VOL. 441, NO. 4; JULY 11, 2014

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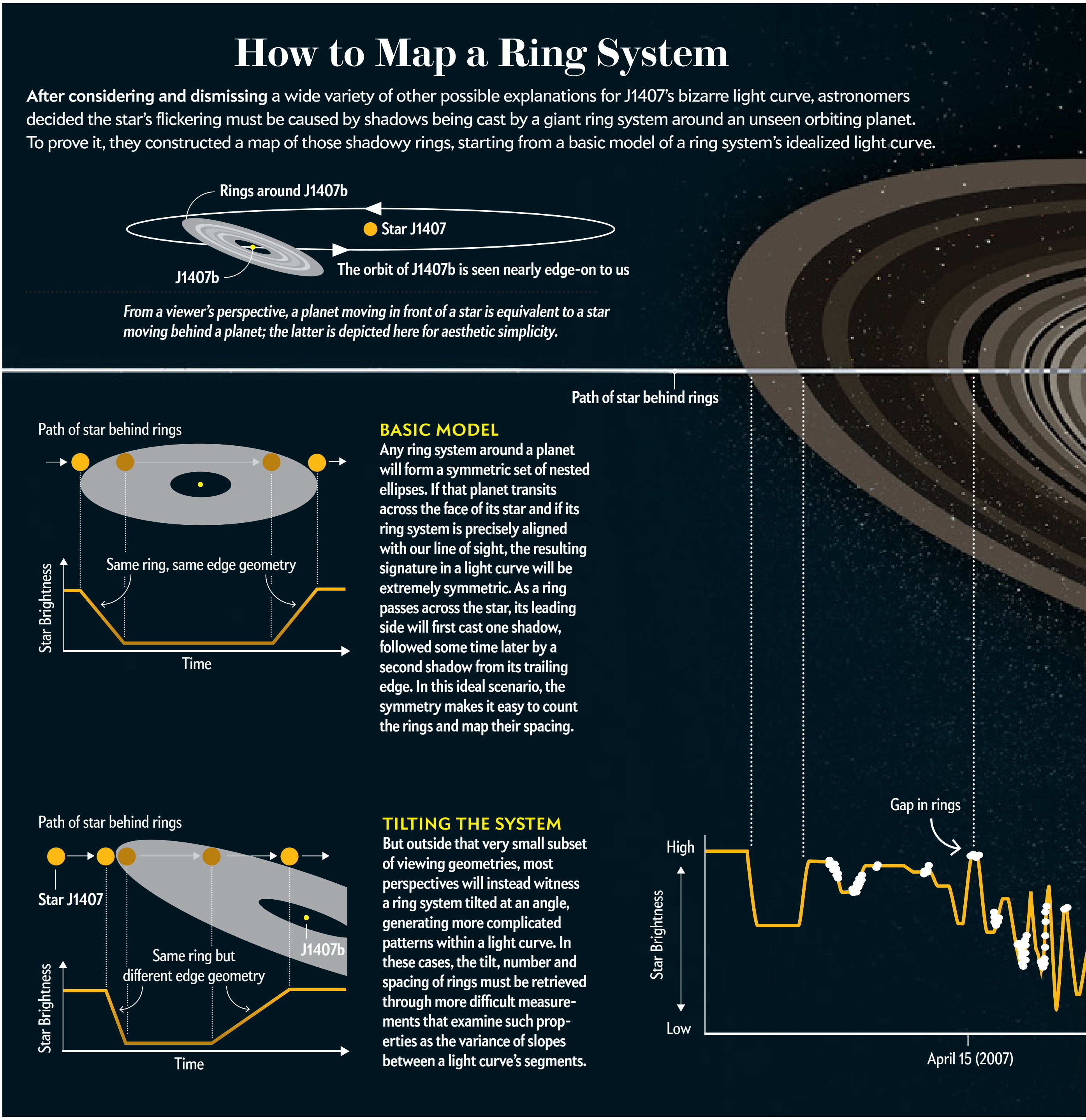

and-fro tugging of that unseen orbiting world. We also enlisted a network of professional and amateur astronomers (including the American Association of Variable Star Observers) to monitor J1407's brightness each night, looking for the dimming that would signal the onset of another eclipse.

We found nothing. This result did not mean that the planet was nonexistent; even if it was 12 times more massive than Jupiter, we would have easily missed it. We could also have looked at the wrong time, when the planet would have been behind its star and invisible to us. Even so, these null detections did allow us to rule out some varieties of low-mass companion stars as the causes of J1407's dimming.

THE RINGS, UNVEILED

DESPITE THE UNCERTAINTY, we forged ahead, trying to surmise the architecture of the rings we suspected were swirling around

Illustrations by Nigel Hawtin (schematics) and Ron Miller (J1407b ring system)

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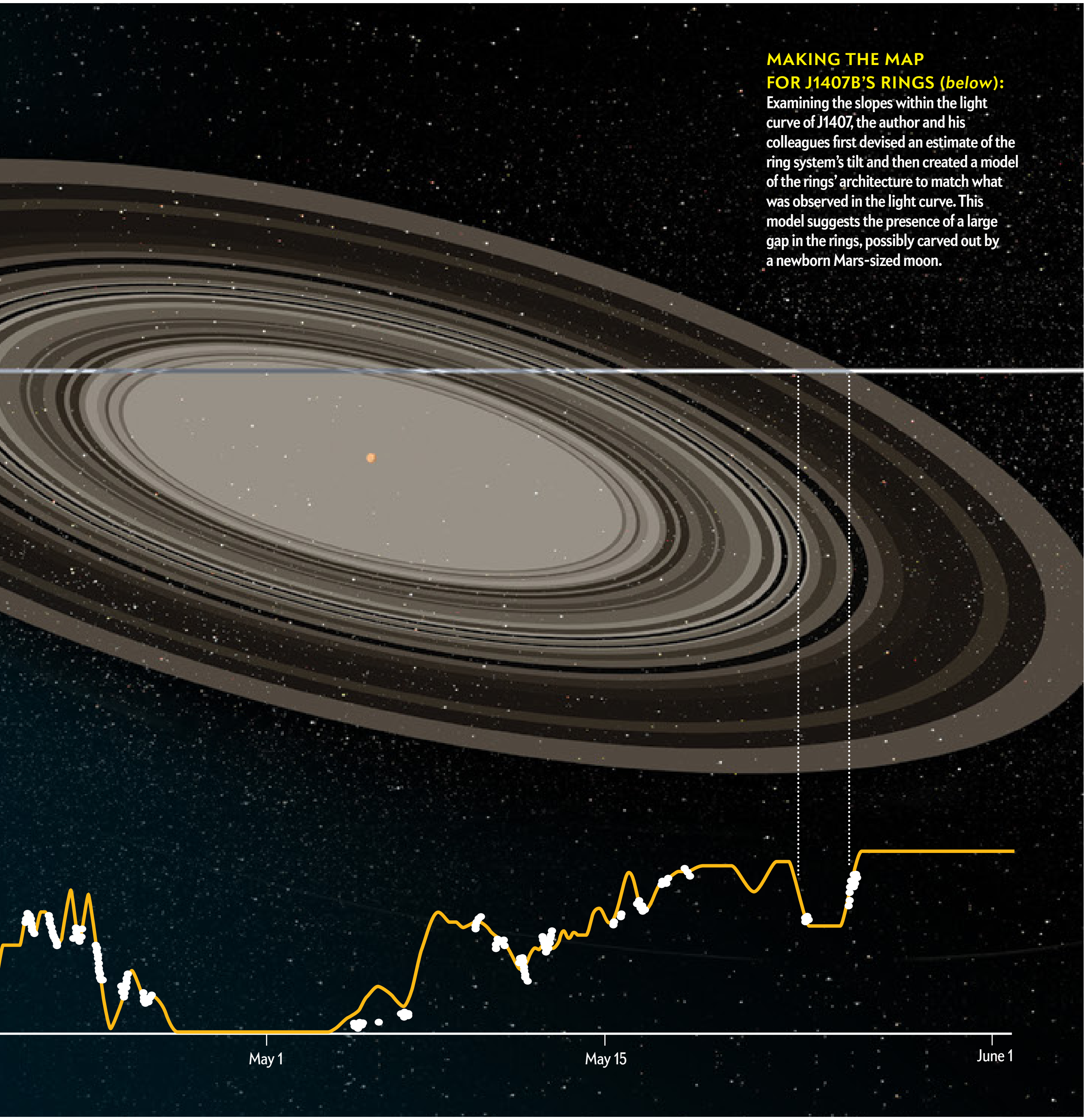

MAKING THE MAP FOR J1407B'S RINGS (*below*): Examining the slopes within the light curve of J1407, the author and his colleagues first devised an estimate of the ring system's tilt and then created a model of the rings' architecture to match what was observed in the light curve. This model suggests the presence of a large gap in the rings, possibly carved out by a newborn Mars-sized moon.

J1407b. For months our team developed computer models that would extract information about the makeup and three-dimensional structure of the rings from the J1407's light curve.

Standing and talking about the problem with several colleagues in front of a whiteboard, we suddenly had an insight: even though we did not know the exact number and placement of individual rings, the steepness of the light curve's sloping segments could give us clues to the ring system's overall geometry, such as its alignment with its star. Using this additional piece of information, we could now complete our computer model for the rings and generate synthetic light curves based on a number of different hypothesized tips and tilts for the rings. Sure enough, one configuration we tested matched the distinctive dips and jags we were seeing in the J1407 data!

Armed with this knowledge, we mapped the ring system, matching each part of the light curve to different ring distances

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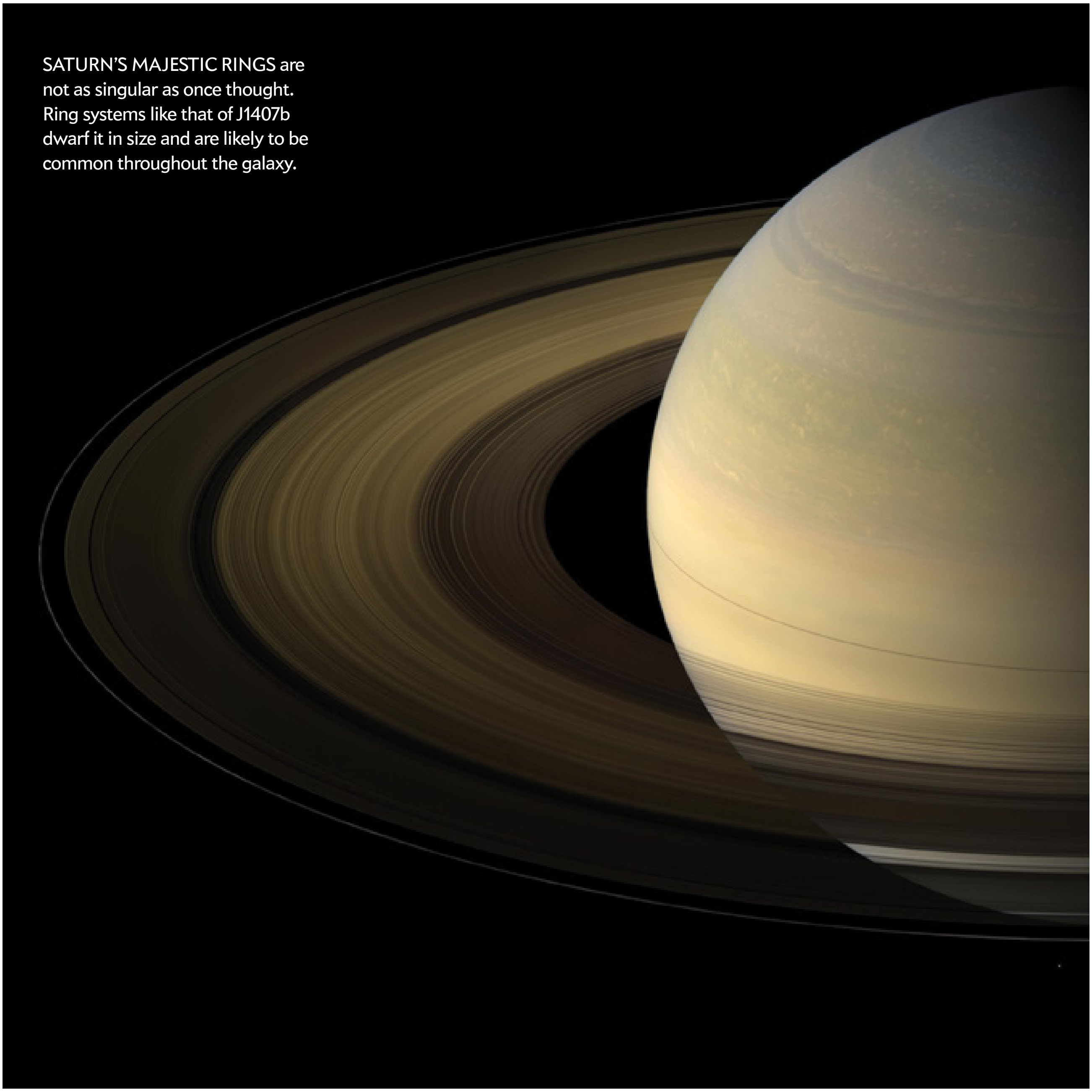

SATURN'S MAJESTIC RINGS are not as singular as once thought. Ring systems like that of J1407b dwarf it in size and are likely to be common throughout the galaxy.

from planet J1407b. Each time the light curve's slope changes, this switch marks the advent or the conclusion of a ring's transit. Counting up all these points in the light curve, we saw at least 24 rings—though considering gaps in the data created by occasional poor observing conditions, we estimated that the system is more likely to have at least 100 rings.

We are fortunate to see J1407b's ring system at this stage in its evolution. To understand why, consider our familiar Saturn and how its ring system has evolved over time. The solid appearance of its rings is actually an illusion. They consist of particles of ice that trace circular orbits around the planet. Those particles, in aggregate, are sculpted by tiny moons—moonlets—that orbit within and just past their outer edge. It is thought that Saturn once had larger rings, but the small particles at the system's outer edges clumped together through their mutual gravity in a runaway process that formed some of the Saturnian moons familiar to us now. This vista would have been as beautiful as it was fleeting—any observer would have been lucky to live in just the right slice of cosmic time to see it.

Like Saturn's ring system long ago, that of J1407b seems today to be in transition. Our model suggests that the system contains a large gap, probably formed by something astronomers have never seen before: a moon—a newborn exomoon—circling J1407b. Our calculations suggest that the moon takes almost two years to orbit J1407b and may have the mass of Mars. Although this large gap cannot by itself constitute a de-

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SCIENTIFIC AMERICAN ONLINE Watch a video about the process of mapping rings at ScientificAmerican.com/jan2016/exorings

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finitive exomoon detection, if the existence of J1407b and its ring system is confirmed, the gap will be the best evidence to date for the existence of these elusive, long-sought objects.

The emerging picture of this exotic, dynamic system is nothing short of spectacular. Flying in from interstellar space, you would see the glare of the primary star almost overpowering the dull glow of its cooler (but still red-hot) planet. Approaching the planet from above, one would see the rings as bright ripples spreading out against the dark backdrop of space. Wreathed with fans of debris produced by collisions, the ring plane would be awash with undulating waves of clumping material. Some of those waves would break at the great gap produced by the largest clump between two rings, the Mars-sized moon.

If the moon orbits slightly out of the ring plane, then by standing on its surface, you would see the surrounding rings arcing against the heavens all around you. And if the moon possesses an atmosphere, errant ring particles would burn from frictional heating as they passed through, filling the skies with majestic showers of sizzling meteors. Overhead, the planet J1407b would be set like a small jewel amid the glare of scattered light from its sprawling rings, crisscrossed with dark cloud bands and glowing like a burning coal.

This system offers astronomers much more, though, than the possibility of pretty scenery. Gas-giant planets orbiting close to their stars are among the easiest worlds to detect beyond our solar system, but lacking solid surfaces, they provide poor prospects for life as we know it. A large moon around such a planet would be a different matter entirely because it could provide a relatively life-friendly rocky, water-bearing surface. If our solar system is any guide, our galaxy could teem with trillions of large moons orbiting giant planets. Proving the existence of moons around extrasolar gas giants would greatly expand the possibilities for places where life could exist.

For years a small cadre of researchers has been ardently searching for exomoons, chiefly through the indirect effects they can have on the motions of their parent planets. Transiting planets provide a precise and periodic dimming of their parent star, but the mass of a large unseen exomoon causes an additional drift in the otherwise regular eclipse schedule. Astronomers such as David Kipping of Columbia University have carried out intensive searches for exomoons, looking for this signature within the light curves from transiting worlds found by NASA's planet-hunting Kepler satellite. To date, they have found no exomoons. But J1407b's possible moon suggests that these ongoing searches shall not remain fruitless for long.

For now, however, both the planet and its moon are only hypothetical. The largest telescopes and most sensitive instruments on Earth have not yet been able to find conclusive evidence irrefutably confirming their existence. Instead that evidence may come from archival data gathered by much cruder technology in years past—such as a collection at the Harvard-Smithsonian Center for Astrophysics.

BACK TO THE FUTURE

THE CENTER HOSTS many researchers, and its offices and corridors are busy with people poring over data from space telescopes, writing papers, running simulations and attending talks. Just a few meters away from this bustling building are the Harvard Plate Stacks, housed in a quiet, brick-walled annex where few people venture. Off in one wing, stacks of large paper envelopes on long shelves fill the walls of three floors all the way up to the ceiling. You might think that it is a secondhand record store, but instead of vinyl disks, these envelopes contain more than half a million photographic plates from various observatories—a quarter of all the astronomical photographic plates in the world. They record a century of night-sky observations.

These photographic plates are now being scanned by the Digital Access to a Sky Century @ Harvard project, which aims to digitize and upload all the data stored on these fragile glass slides. We have determined that J1407 appears on about 700 of these plates, in images taken from 1901 to 1984. With the data from these plates, we will be able to search for more eclipses so that we might learn when the next one will occur.

Right now our best guess is that it will happen sometime in the next decade. Meanwhile we are still hunting for definitive proof of the planet and its rings, and dedicated astronomers monitor J1407 almost every night. They are looking for the dip in starlight caused when the outermost ring begins to pass across the star. When that happens, many observations can be carried out to study the rings in much greater detail. When the rings move in front of the star, we can use spectrographs on the world's largest telescopes to collect some of the starlight shining through and around the rings to discern their chemical composition and how that composition changes with distance from J1407b. Most excitingly, J1407 is a relatively bright star visible from the Southern Hemisphere and is easily observable—astronomers with small telescopes can follow the brightness fluctuations of the star in real time to provide 24-hour continuous coverage from around the world.

Our deep dive into the giant rings of J1407b will be only the beginning of a broader series of investigations relating to how solar systems form. Newborn giant planets are thought to give rise to circumplanetary disks that condense into moons and rings, and we expect to soon detect more of these systems by the shadows they are surely casting far across the galaxy. Now that we know what we are looking for, the race is on to find more giant ring systems and exomoons like the ones thought to exist around J1407b. My colleagues and I are already scouring new databases for telltale signs of additional ring-bearing planets in other systems. Saturn's gorgeous system of rings may soon have stiff competition from those around other stars. SA

MORE TO EXPLORE

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Better Than Earth. René Heller; January 2015.

In Search of Alien Jupiters. Lee Billings; August 2015.

scientificamerican.com/magazine/sa

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PEOPLE WASH their hands with arsenic-laden water at a village pump in Kolsur, India.

PUBLIC HEALTH

DEATH IN THE WATER

Arsenic poisoning from wells is getting worse in India and other parts

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of Asia, harming millions while scientists scramble to find safer sources

By Katy Daigle

Photographs by Paula Bronstein

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Katy Daigle is an environment writer based in New Delhi.

On her wedding night, Gita Paul felt doomed. Her parents had arranged her marriage to a man she had never seen who lived in Kolsur, an impoverished village kilometers from her own home in this landscape of rice paddies and cattle paddocks and clusters of homes, near the eastern Indian city of Kolkata. Arranged marriages to strangers are common in the region. But when Gita laid eyes on her husband, she was horrified to find him covered in open lesions and scabs. Then she met his family. An elder brother had lost a foot to rot, a sister was sickly and another brother had died in his 30s. Many people in the village were ill. "I'd never seen anything like it," Gita says, years later, during an interview, sitting on the rough steps of her family's tiny brick-and-mortar home. "I thought it was a contagious disease."

By the time scabs appeared on Gita's skin, she had heard that the illness was not airborne—it was in the water. Scientists had come by with simple testing kits and with the bad news that the cool, clear water from the village wells was making people ill. It was poisoned with arsenic. Gita decided that she and her husband had to move. They spent all the money they had to relocate to a neighboring farming village. But people there were also dying, and villagers said the wells there were tainted, too.

The scientists and the villagers were right. In many of the region's villages, people were unwittingly poisoning themselves by drinking the water and cooking meals and washing their dishes in it. At least 140 million people in Asia are drinking arsenic-contaminated water. It pours out of countless tube wells, hand-cranked pumps attached to plastic or metal pipes sunk into the earth. More than 18 million of these small wells have been dug across India alone, often by hand, over the past three decades, according to government census figures. They were sunk in an attempt to bypass surface waters teeming with illness-causing bacteria or infused with industrial runoff. But death also lay underground.

The naturally occurring arsenic kills human cells, leading first to skin scarring and then, as it slowly builds up in the body, to brain damage, heart disease and cancer. Arsenic-laced groundwater has been found in at least 30 countries, from Argentina to China, Cambodia and Vietnam, as well as parts of Canada and the U.S. [*see map on page 48*].

Now the ever expanding use of groundwater wells—people need water to drink, and farmers need it to grow crops to feed a large population—has been making things worse. Pumping out this water has changed the courses of underground streams, so previously clean water now flows through arsenic-laden sediments, and wells that used to be pure in villages once healthy suddenly pump out catastrophes.

Scientists have recently been trying something new: mapping the underground landscape in an attempt to pinpoint safer places to sink the wells. But so far the subterranean flow changes and rates of chemical reactions have been outpacing the predictive ability of the maps. "It's a pathetic situation. It's just desperate," says Dipankar Chakraborti, an environmental analytical chemist who has devoted 28 years to studying the problem at Jadavpur University in Kolkata, where he formerly headed the School of Environmental Studies. The university is now working to set up a research institution in his name—the DC Research Foundation—to further arsenic studies. "We're changing things so quickly underground, we can barely keep up."

THE WELL PROBLEM

WEALTHIER AREAS AFFECTED, such as the southwestern U.S., have the money and means to filter their water. But many of the worst-hit populations are also the world's poorest. In South Asia—considered one of the highest-risk zones—groundwater steeped in arsenic runs across a densely populated swath of land covering parts of India, Nepal and Bangladesh. Although the World Health Organization says arsenic concentrations are dangerous above 10 micrograms per liter of water, India's legal maximum re-

IN BRIEF

Drinking wells in the poorest, most populated areas of the planet, dug to bypass surface bacteria, are poisoned with arsenic from deeper groundwater.

Shifts in the flow of aquifers, driven by a booming population's heavy water use, are contaminating previously clean wells and harming people.

Mapping underground features, combined with data on their soil and water chemistry, could help predict danger zones. But reliable mapping is hard.

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VICTIM: Srivas Paul, poisoned with arsenic from contaminated well water, rests in the village of Kolsur. The lesions on his body are symptoms of the poison.

mains 50 micrograms per liter—and many wells test far above even India's lenient standard.

The troubles in India date to the 1960s, when the country began drinking groundwater as an alternative to being poisoned by bacteria-infested surface water, often stagnant and unprotected from sewage or agricultural runoff. In 1969 India launched a $125-million program, aided by international groups such as UNICEF, to drill holes into the earth and sink more than a million simple wells. More programs followed. There seemed little other choice. India had almost no infrastructure for storing, distributing or filtering water—a situation that remains today, except in the largest cities.

The tube wells were hailed as an inexpensive and lifesaving solution. Of India's 1.25 billion people, about 80 percent of the rural population and 50 percent of the urban population use groundwater for drinking, cooking, and irrigating crops and garden plots. Groundwater solved another acute problem: famine, which had threatened parts of the nation through the 1980s. Today India uses a staggering 91 percent of its irrigation water to grow rice, wheat and sugarcane.

But the agricultural boon came with consequences. Most tube wells were sunk to depths of 50 to 200 meters, stopping when they reached the first layer of bacteria-free water. Unfortunately, this depth corresponded precisely with where most of the region's arsenic is found, something not known at the time. Drill a bit farther, and the water is usually potable. But drilling deeper wells takes more time and money, requiring sturdier materials that many impoverished villagers cannot afford.

There have been other obstacles. Widespread ignorance and institutional apathy stymie efforts to educate people about the risks. Seemingly simple solutions, such as harvesting rainwater or treating water on the spot, prove too complex for the illiterate and are easily misunderstood. Harvesting efforts break down as plastic tarps and pipes are poorly maintained. Filtering water though sand-filled buckets is often seen as an onerous and time-consuming chore. Treatment tablets passed out by scientists and activists are misused by villagers who cannot read instructions or understand the chemistry. More permanent solutions, such as large-scale filtration plants that could eliminate the guesswork for millions, have proved both costly and technologically cumbersome, suffering many of the pitfalls of poor oversight.

"The best solution, of course, is to avoid the contaminated water altogether," says Michael Berg, who heads water contamination research at the Swiss Federal Institute of Aquatic Science

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WATER HAZARD: This pond, near Berachampa, India, is used by villagers for swimming and for washing clothes, although arsenic has been detected in the area's groundwater.

and Technology, known as Eawag. "But compared with surface water contaminated with pathogens, the groundwater is seen as the lesser of two evils."

GEOLOGY OF A KILLER

ARSENIC is a relatively common element. Tasteless, colorless and odorless, it was long a favorite tool for assassins. It is toxic to most life-forms, even at very low doses.

The plains below the Himalayas are some of the most arsenic-rich lands on earth. After the giant mountains were formed through tectonic collisions, arsenic-laden pyrite minerals in their slopes were exposed and eroded away by swift-flowing rivers, whose waters carried the sediments through India, Bangladesh, China, Pakistan and Nepal. As the dissolved arsenic churned through the water, it underwent chemical reactions to combine with oxygen and iron or other heavy metals, forming granules that fell to the riverbed and leaving striated layers of arsenic-infused soils at random depths. Over millennia the muddy depos-

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its built up the ancient deltas of the Ganges-Meghna-Brahmaputra plain—now a densely populated area of some 500 million people covering almost 700,000 square kilometers of land.

By the natural order of things, most of that arsenic should have stayed underground. But the tube wells tapped into it, even in places where rivers no longer run. “You can’t just look where the rivers are flowing now,” says Chakraborti, tracing out water paths with his fingers while sipping coffee from a laboratory beaker in his university office, where filing cabinets and visitors shelter under a green canopy of potted plants. “You have to consider how the rivers’ paths have changed. At one point, this was all awash in water. That means there are a lot more possibilities for finding arsenic.”

Not all of the earth’s arsenic is leached from soils into water; certain geologic conditions must be present. Scientists studying the problem have outlined two general scenarios that prompt arsenic’s release, and this understanding has opened possibilities for predictive modeling on probable risk.

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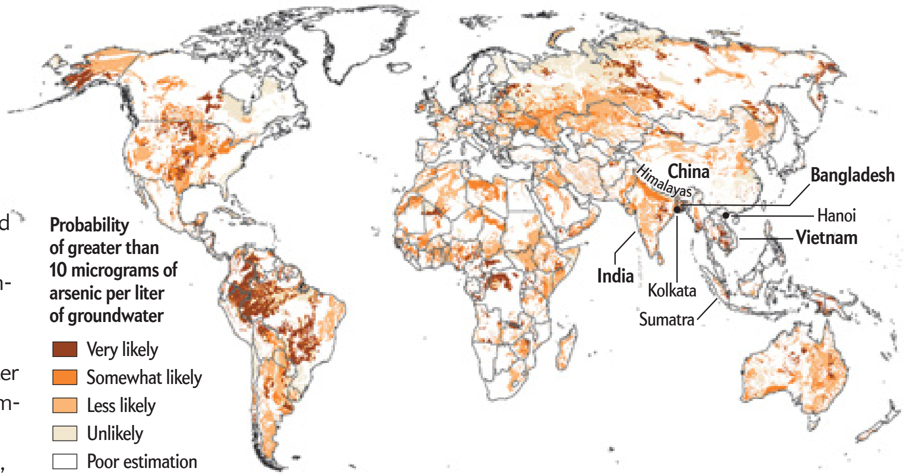
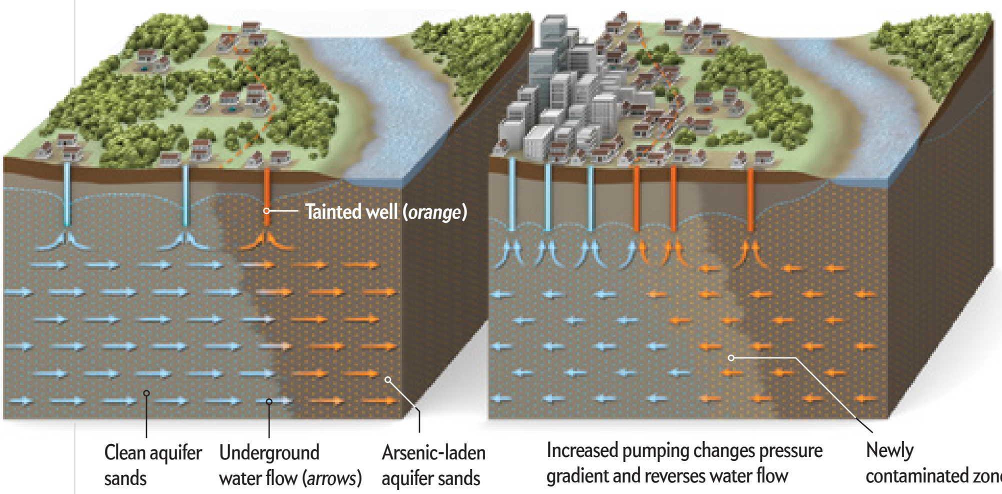
Tracking Underground Arsenic

A naturally occurring element, arsenic can be found in minerals within soil and rocks all over the world, usually bound together with particles of metal. In contact with underground water, arsenic can break free in concentrations high enough—at least 10 micrograms per liter of water—to harm human health. Chemical reactions leading to the breakouts can be triggered in two ways. High-pH, or basic, water circulating through soils can free the element, as can oxygen-depleted water moving through soils rich in organic carbons. By analyzing water and soil conditions in various parts of the world, scientists try to predict the places most likely to be in danger.



Poisoned Soil Is a Global Issue

Researchers at the Swiss Federal Institute of Aquatic Science and Technology (Eawag) created a world map of arsenic risk based on arsenic-releasing soil conditions. The combination of oxygen-rich soil and high-pH water makes parts of Argentina and Chile likely hotspots. Soils with abundant organic carbon but low oxygen levels, common in river delta regions such as northern India and Bangladesh, as well as the Amazon basin, raise risk there. (Amazon data are not completely reliable, however.)



Development Can Increase Contamination

When a growing population pumps lots of water from the ground for irrigation and drinking, it can change the direction of underground water flow and arsenic contamination. For instance, Hanoi in Vietnam pulls water from an arsenic-free aquifer that used to flow away from the city. The flow pushed away water from a nearby, connected aquifer that was already contaminated with arsenic. Because of recent population growth, however, Hanoi began sinking extra pumps into the clean aquifer. The water pressure dropped lower than pressure in the dirty aquifer, so the flow began to reverse, and tainted water moved closer to the city.

The first scenario—alkaline arsenic release—takes place in oxygen-rich soils, where water with an alkaline high pH is circulating, such as in arid regions of Argentina or the southwestern U.S. The water triggers a chemical reaction that breaks apart oxidized iron and other metals coating soil particles. That frees any arsenic that had bonded to those charged molecules, allowing it to dissolve and contaminate surrounding groundwater.

The second scenario—reductive arsenic release—takes place in soil low in oxygen but rich with organic carbons. These conditions are typical in deltas, floodplains and river basins, where surface soil is often new enough to still be infused with bacteria. These conditions correlate with some of the world's most populated lands, including northern India, Bangladesh and Southeast Asian countries such as Vietnam. In this case, the bacteria promote the chemical reactions using catalyzing enzymes to bust up iron oxides on which arsenic has bonded. So if one were to take a handful of soil from an area with arsenic-free groundwater—say, in North Carolina—and bury it in Bangladesh, it would release arsenic.

The process goes on as long as there is enough organic carbon to feed the bacteria, growing more scarce at greater depths. Fertilizers, which are used heavily in India, can prolong the process. It can be mitigated by salinity, particularly sulfides, which will also bond with arsenic to create precipitates. But that only holds for as long as the oxygen remains low. Any new oxygen introduced can be used by bacteria to break up the sulfides and, again, release any bonded arsenic. So if aquifers are depleted and re-

SOURCES: "STATISTICAL MODELING OF GLOBAL GEOGENIC ARSENIC CONTAMINATION IN GROUNDWATER," BY MANOUCHEHR AMINI ET AL., IN *ENVIRONMENTAL SCIENCE & TECHNOLOGY*, VOL. 42, NO. 10; MAY 15, 2008 (*map provided by Michael Berg*); "RETARDATION OF ARSENIC TRANSPORT THROUGH A PLEISTOCENE AQUIFER," BY ALEXANDER VAN GEEN ET AL., IN *NATURE*, VOL. 501; SEPTEMBER 12, 2013 (*Hanoi case study*)

Illustration by Emily Cooper

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charged at a rapid pace, sending freshly oxygenated water trickling back into the ground, that circumstance can prompt a new wave of arsenic release. Recharging aquifers is also common in India, providing perfect conditions for the ongoing release of arsenic over long periods.


ARSENIC CHASER: "We can barely keep up," says Dipankar Chakraborti, a chemist at Jadavpur University who studies how the chemical moves through aquifers.

MAPPING THE DANGER

AT THE MOMENT, most contaminated wells are found through a time-consuming, labor-intensive process of going village to village and testing each well with a chemical-reaction field kit. After the water is mixed with several reagents, a testing strip is inserted into a sealed container to absorb any arsenic released. The color of the strip after about 10 minutes gives a ballpark result: white indicates the water is clean; red shows it is tainted.

But the field kit offers only a blunt test that can detect contamination to a certain level. Beyond that or for more detail, the water needs to be tested in a lab.

Because the crisis is so widespread, inspectors rarely detect the problem in time, instead arriving at wells years after people have been drinking arsenic-laden water. So some scientists have begun to seek shortcuts, studying satellite images of land contours and mapping water flows to predict the types of sediments underground and to show where arsenic is most likely to be found. They say such methods can help governments save money and time by narrowing the number of tube wells that need testing, or they can raise red flags in areas previously thought safe.

In 2006 Berg and other scientists at Eawag began creating a global map of arsenic worldwide based on early predictive models built on parameters such as soil content, land slope and water flow. They published the first draft of their global risk-probability map in 2008 and plan a newer version incorporating the latest studies and more details soon.

These models "can make predictions where no testing exists," says Berg, who has been leading the effort. For example, his team was able to predict that large areas of Sumatra, Indonesia, were in danger. "Then we went and tested, and our prediction was confirmed. That gave us a lot of confidence that this predictive modeling was not so bad."

In 2013 the China Medical University teamed up with Eawag to build a China model after tests on some 445,000 tube wells in 2001–2005 revealed about 5 percent were contaminated above the Indian legal limit of 50 μg/L; many more exceeded the more conservative safety level set by the World Health Organization. With vast areas of the country still untested, the team wanted to help policy makers take action. "There is a barrier between science and society. Somehow we need to show policy makers that we can help solve real problems," says Luis Rodríguez-Lado, a chemist now at the University of Santiago de Compostela in Spain and lead author on the paper, published August 2013 in *Science*. The China model, when compared with actual tube-well measurements, correlated 77 percent of the time. Such data, Rodríguez-Lado says, can help save lives, money and time by highlighting which tube wells need testing: "That's hugely satisfying for any scientist."

There are limits, however. Because the models are based on surface conditions and recent knowledge about water flow, they are poor predictors of the contents of more ancient and unknown underground water bodies. "Our predictions are always related to what you see at the surface," Berg says. "If they are related to older deposits, we cannot catch that."

Building the models on accurate and up-to-date information is crucial for avoiding mistakes, Rodríguez-Lado says. He had gone into the China study assuming the model would follow alkaline conditions, with oxygen-rich soil and basic water, based on China's arid landscape and rainfall patterns. "Most of China was classified under oxidizing conditions for arsenic release," he says. "But the information from China was poor," and he quickly realized China's aquifers were anoxic, like those in India and Bangladesh. When he recalculated using these parameters, accuracy improved.

There are other limitations to predictive mapping, particularly in resolution. The China risk model set its grid sizes at 25-by-25 kilometers—too large to predict which villages will be hit. "The models can be useful, but they're not quite there," says geochemist Alexander van Geen of Columbia University's Lamont-Doherty Earth Observatory. "Suppose a model predicts there is a 20 percent chance of arsenic in a certain area. Well, I'd still want to test my well, right?"

FAILED SOLUTIONS

GOVERNMENTS HAVE ATTEMPTED other ways to solve the water-supply problem, but they have failed to make a dent. A few years ago the West Bengal state government built a pipeline to carry Kol-

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PUMP TROUBLE: In the town of Kalyani, India, children pump arsenic-contaminated water, used for drinking and cooking, from a tube well (*above*). Simple treatment plants to remove the chemical, such as this one in Kolsur (*right*), have been poorly maintained by the government; the one here is broken.

kata's arsenic-free municipal water east to rural villages. But the water runs only a few hours a day, if at all, and it does not reach every village. The black, plastic pipes are poorly maintained, and many lie broken, spilling water through jagged holes into muddy puddles by the side of the road.

Hundreds of arsenic-removal plants, each costing an average of about $1,500, have been installed across both West Bengal and neighboring Bangladesh. Chakraborti and others have shown that the simple, cylindrical filter mechanisms have been largely ineffective. One study found that only two of 13 plants from several manufacturers maintained arsenic levels below the Indian standard. None reliably met the WHO standard. By the time the study was published in 2005, that barely mattered: poor maintenance and oversight meant only three out of a total 18 plants were still working.

Digging deeper tube wells to bypass current layers of contamination is not only an expensive task, stretching village resources, but Chakraborti's research shows it is only a short-term fix. The low-lying aquifers, at 200 meters under the surface, are partly blocked off from higher, poisoned ones by a thick clay barrier. "Partly" is a key caveat. There are cracks and holes. So drawing from greater depths may buy time, but deadly waters can eventually trickle down and contaminate what is below.

This is already happening in India, where groundwater use is so intense that 60 percent of the country's aquifers will hit critical levels in 20 years unless the pumping is drastically curtailed, the World Bank says. In the Bengali village of Jaynagar, Chakraborti found once safe arsenic concentrations at eight tube wells had jumped drastically to perilous levels in just five years, from 1995 to 2000.

Arsenic also can move horizontally, from one dirty aquifer to a

SCIENTIFIC AMERICAN ONLINE Watch researchers describe an irrigation-arsenic link at ScientificAmerican.com/jan2016/water-arsenic

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GROWING PROBLEM: In this rice paddy outside Kolsur, as elsewhere, there is an increased need for irrigation despite bad water.

neighboring clean one, as well as up and down if the water pressure between the two reservoirs changes. This movement is currently imperiling Hanoi, which pulls its water from an arsenic-free aquifer that used to flow away from the city. That flow pushed water from a neighboring contaminated aquifer away. But as the Vietnamese metropolis has grown, it has drawn more and more water from the safe layer, and the change has reversed the flow. Water from the tainted aquifer, near the Red River, has begun to pour into the city's previously clean one [*see box on page 48*]. This is cause for worry, van Geen says, but he notes that so far the problem is developing slowly. His study found that arsenic is moving 16 to 20 times more slowly than the water itself, presumably still bound to other elements in the soil and only gradually being freed by underground chemical reactions.

In India, things have moved much faster, accelerating with the size of the country's population and the effort to feed its people. Hardly anyone is policing a 1986 law barring excessive use of groundwater. Even where fields are located next to lakes or rivers, farmers irrigate with groundwater. Even when no water is needed, landowners pump what they can to sell on the black market. And the arsenic is getting into the food chain. It is in the rice. It is in the cow milk and buffalo meat. Chakraborti has even found it in bottled sodas and vials of sterile water used by hospitals.

STRUGGLING FOR SAFETY

SO ALTHOUGH RESEARCHERS AGREE on the problem and the cause, van Geen says that "what isn't clear is what to do about it." Along with Chakraborti and others, he believes that while predictive modeling may be useful, it cannot replace the need for testing tube wells on the ground.

Van Geen advocates using inexpensive testing kits at the sites of the wells. They are not as accurate as lab tests but give immediate results at minimal cost. He has also uncovered a potential job market in testing. A study of 26 villages in the state of Bihar found that about two thirds of residents were willing to pay 20 rupees, or about 30 U.S. cents, for someone to test their wells.

"We can't handle all these private wells, so our angle is to promote a network of testers and give them a financial incentive for providing tests," van Geen says. In Bangladesh, he and his colleagues managed to have enough wells tested and plotted with GPS location data to build a dynamic map of the country's safe and unsafe wells so villagers can easily find safe water.

Follow-up research also suggests that villagers who pay for testing are more likely to heed the results and switch to safer though less convenient wells, according to one of van Geen's research partners, hydrogeologist Chander Kumar Singh of TERI University in New Delhi. The two are also studying how socioeconomic factors such as income or caste identity might keep people from using safe wells shared by other castes or those with less money. "We haven't seen much concern from the government," Singh says. "Maybe some of our work can help point the way."

Chakraborti similarly has trained helpers to travel by bicycle or train to villages to collect well samples. He has organized international conferences and led teams of doctors, students and activists out to do health checks. He has also set up a fund to cover his research and free water tests for poor residents. And when Chakraborti's credentials fail to impress villagers, he sets aside his distaste for India's old hierarchies and plays up his upper-caste Brahman heritage: he dons the white loincloth and sacred threads worn by Brahman holy men and points families to currently safe wells. "I hate it, but I'll do it," he says of the stunt. "All I have to do is get through to the mother. Then I know the family will be okay."

In Gita's village, her frail husband, Srivas, struggles with headaches, constant pain and exhaustion. Calloused lesions cover his body, and his skin stings, especially in the sun. There is no known cure for arsenic toxicity. There are no drugs to reverse the chromosomal damage done. Chelation therapy, which involves injecting bonding agents into the blood, has been used historically in extreme cases of metal poisoning. But it is highly risky and prohibitively expensive in India. The best most can manage is to eat nutritious food and stop ingesting the poison. Still, Srivas counts himself among the lucky. He has a teenage son who helps to haul buckets of healthy water from a nearby hospital clinic, and Gita earns the family's income in her job as a maid.

"I have no complaint against anyone," says a trembling Srivas, reflecting a fatalism that is so common among India's poor that some scientists worry it actually keeps villagers from searching for cleaner wells. "Even if I did want to complain, there is no one to listen." SA

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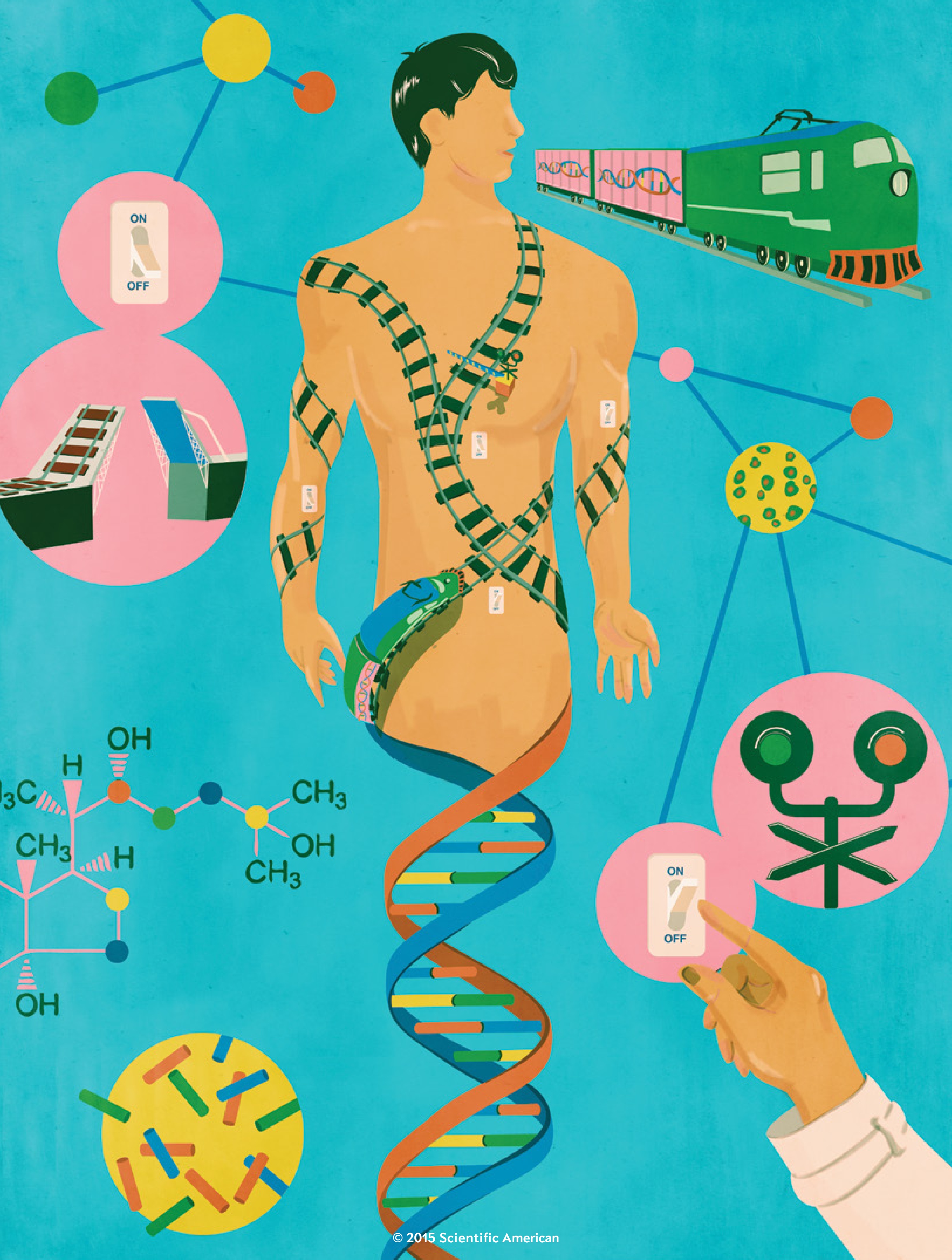

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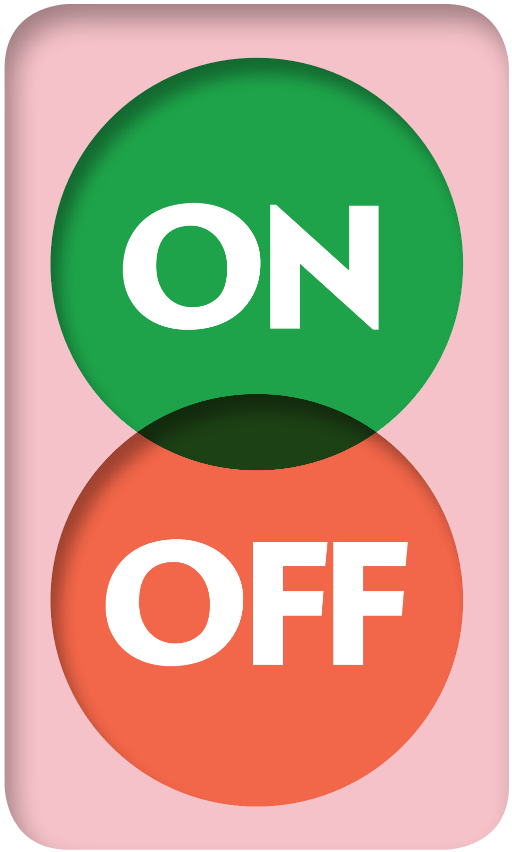

SWITCH FOR GENES

Researchers are developing molecular switches that can inactivate transplanted genes, paving the way for safer gene therapies. First up—better treatments for cancer

By Jim Kozubek

Illustration by Giordano Poloni

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Jim Kozubek is a computational scientist and writer who lives in Cambridge, Mass.

HUMANS DON'T MOLT," R.J. KIRK TELLS ME. KIRK IS A BILLIONAIRE GEEK WHO runs his offices out of West Palm Beach, Fla., a balmy land of pelicans and tangled mangroves. He built his fortune on conventional medications that can be taken as a pill, and I had phoned to talk about his newest endeavors in biotech. I wasn't expecting to hear about bugs. But the molting process, in which a growing insect builds a new exoskeleton to replace an old one that no longer fits, turns out to have some very important properties that can be adapted to make gene therapy, still a largely experimental procedure, safer.

Doctors would like to deliver copies of working genes to people to treat a variety of hereditary ills. Genes provide cells with the instructions for manufacturing proteins, among other things, and so inserting a functional gene into the body can, in theory, provide a lasting supply of whatever missing proteins a patient might need. But gene therapy has had a troubled history, in part because scientists cannot precisely control where a new gene inserts into a cell's DNA and how active it is once there (which determines how much protein is produced). These problems can lead to unwanted side effects—including the development of malignant tumors.

A logical solution to the problem of having proteins made in undesirable places and amounts would be to combine a therapeutic gene with a switch that could reliably turn it on or off as needed. As it happens, says Kirk—who is chairman and chief executive officer of Intrexon, a company that is developing new genetic engineering techniques—insects routinely use just such a switch to control molting.

Here's the thing. Insects do not just sort of molt, starting and then stopping partway; they either do it, or they don't. The genetic pathway that drives the process must remain completely turned off until the time is right. The gene that interests Kirk serves as the master switch for all this activity. It codes for a hormone called ecdysone. As ecdysone surges through the insect, it turns on a raft of other genes to start building the new exoskeleton. After the new exoskeleton is ready, the insect discards the old one. Once molting is nearing completion, the levels of ecdysone fall to zero—at which point the genetic pathway turns off. More important, from Intrexon's point of view, the switch is airtight when turned off—molting does not happen in the absence of ecdysone. The switch does not allow this group of genes to act together again until molting is set to begin.

The scientists at the company decided to take advantage of this foolproof characteristic to tightly control any genes transplanted into people. Imagine equipping each replacement gene with a biological switch that turns on—and thus activates the therapeutic gene—only in the presence of ecdysone molecules that have been adapted to work with human physiology. Patients given low doses of this activating drug (technically known as a ligand) could turn on only a few copies of the new gene, thus producing low amounts of whatever compounds were encoded. Patients given high doses of this activating drug could

IN BRIEF

Early experiments in gene therapy ran into problems, in part because researchers could not control how active newly inserted genes would become.

Researchers are addressing the issue by developing molecular switches that can reliably adjust the function of a transplanted gene by remote control.

Some of these gene switches are already being combined in human trials with experimental immunotherapies to treat cancer.

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turn on many copies of the gene and thus manufacture large quantities of the related compound. In an unexpected emergency, however, withdrawing the ligand would shut the entire process down. No ecdysone, no activity by the introduced gene. As an added bonus, the ecdysone would not interfere with any other genes, which biologists call "cross talk," because the human body does not otherwise use, or need, the hormone to regulate genetic activity. Or, as Kirk puts it, "Humans don't molt."

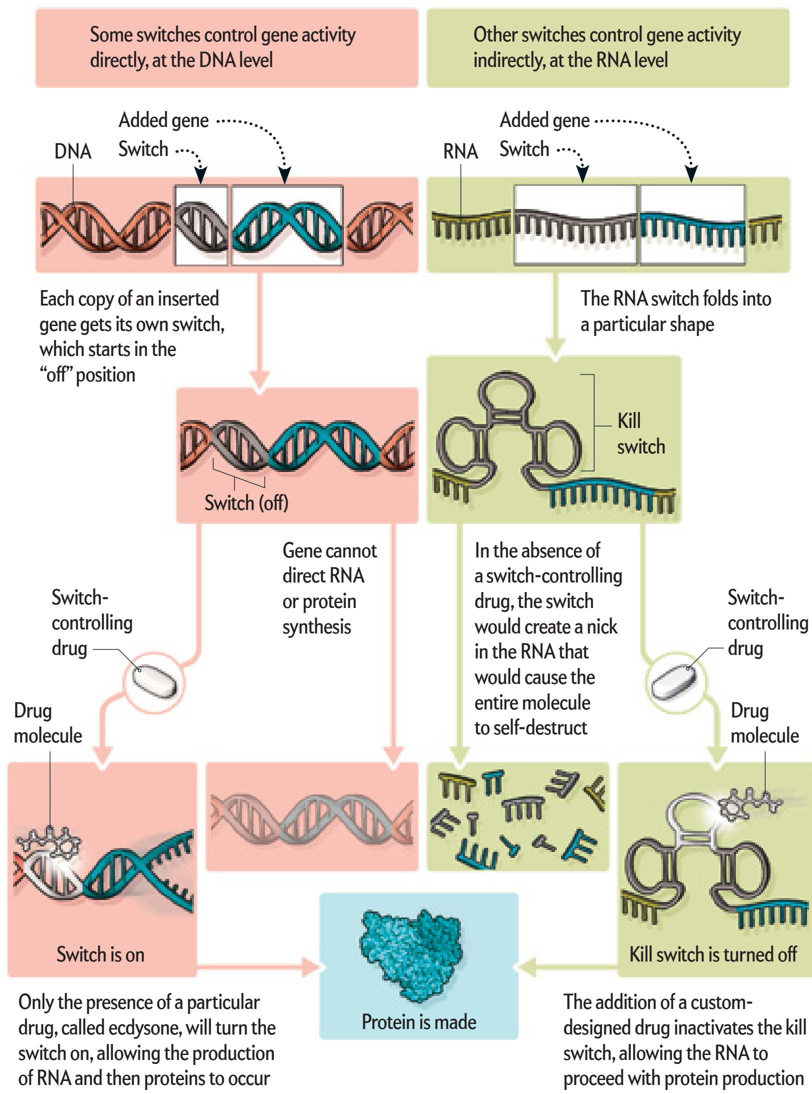
Over the past eight years Intrexon has "wired" its ecdysone switches to thousands of human genes, demonstrating in laboratory tests that virtually any gene in the body can be put under the hormone's control. In addition, Kirk's group has added a second layer of checks by stitching in so-called cell-specific promoters to their switches. Cell-specific promoters are swatches of genetic material that cause genes to turn on (be "expressed") only in specific tissues, such as neurons or blood or liver cells, or only in certain conditions, such as the low-oxygen environment of a tumor. The addition of these molecular gatekeepers further reduces the chances of unwanted side effects occurring in parts of the body that had not been targeted for treatment.

Meanwhile other groups are borrowing from different biological processes to develop their own genetic switches and added control mechanisms. Eventually the ability to deliver several switch-controlled genes—each one able to be dialed up or down as needed—should make gene therapy safe and effective enough that it can become part of mainstream medicine. Or at least that is the idea. Preliminary tests in humans suggest that the switch approach could work as intended. So far it has been studied mostly in cancer and will likely make its biggest mark there first.

HOW IT WORKS

Two Strategies for Controlling Gene Activity with Pills

A major challenge to the development of successful gene therapies is making sure that the newly inserted genes are not too active—which can cause cancer, among other things. All genes, which are made up of DNA, instruct cells to make another molecule, called RNA, which in turn often directs the manufacture of proteins. Researchers are studying various approaches (*two of which are pictured below*) for creating biological switches that can shift a gene's operation (and thus the production of proteins) into gear—or shut it down altogether.



FIRST TRIALS

IN PARTICULAR, investigators are studying the switch approach as a way of making cancer immunotherapy less of a harrowing ordeal for patients. Cancer immunotherapies, which have made a lot of headlines of late, aim either to reawaken an immune response that has been lulled to sleep by chemical signals from a malignancy or to jump-start an entirely new and more powerful anticancer response than a patient's immune system can achieve on its own. Trouble is, a rebooted immune system can easily slip into overdrive, triggering life-threatening fevers and the potentially lethal buildup of fluids throughout the body.

Gene switches are now being evaluated, for example, in

Illustration by Tami Tolpa

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small trials of carefully chosen patients with recurrent melanoma (a type of skin cancer) and breast cancer. Doctors inject one or two tumors in these individuals with genes designed to boost production of cytokines—signaling molecules (such as interferon and various interleukins) that the immune system uses to monitor and adjust the fight against tumors. Investigators believe that they may not need to treat all the malignant lesions in each patient, because once the immune system is properly primed to tackle one nest of cancerous cells, it should start searching for others elsewhere in the body without the need for further prompting.

Cytokines trigger a wide range of physiological reactions—from opening up blood vessels so that immune cells can rush to the scene of an infection to activating ruthless killer T cells, which, among other things, specialize in destroying cancerous cells. But to date, doctors have not been able to treat patients successfully with one of the most powerful cytokines, known as interleukin-12, or IL-12.

INSPIRED BY NATURE: The hormone ecdysone regulates the process of molting, which transforms many insects, such as this butterfly, into their adult form. Now a biotech firm has reworked ecdysone into a much needed safety switch for gene therapy.

This failure stems in part from IL-12's propensity for unleashing a "cytokine storm," in which the immune system seemingly goes on a rampage against the body. In the bloodstream, IL-12 can cause a sharp drop in blood pressure, difficulties with lung function, and heart problems, which together can easily lead to organ failure and death. And yet, says Laurence Cooper, a physician-scientist at the University of Texas M.D. Anderson Cancer Center and CEO of biotech company Ziopharm Oncology, "there is a ton of literature on its effectiveness in the tumor microenvironment. IL-12 is the holy grail of immunotherapy." The idea, then, is to deliver as much IL-12 as possible to a single tumor but not so much that a cytokine storm occurs. Here is where the switch technology could prove revolutionary.

Researchers insert the switch-enabled IL-12 genes into an individual's tumor, where they take up residence in many cells, including the immune cells that are already there, giving the latter a boost. Because the switch can be activated only by the presence of the ligand, physicians can increase the levels of cytokine in the tumor very deliberately by slowly increasing the amount of drug they give their patient. If a cytokine storm starts to develop, they can skip the next scheduled dose, thereby averting the worst of the damage.

Ziopharm, which is working with Intrexon to develop switch-enabled cytokine treatment in people, reports encouraging results so far. Kirk acknowledges that they might have chosen to test their approach on something less potent than the IL-12 gene—where the slightest misstep could prove fatal. But he says, "We chose one of the hardest genes because we wanted to pressure-test the switch." In other words, when it counts most, does a switch that has been turned off remain completely off?

Results from two safety studies conducted at several medical centers (and totaling fewer than 40 patients) suggest that the answer is yes. Although no one was cured, the switch-controlled regimen appeared to be reasonably safe. As anticipated, a few patients did begin showing signs of a dangerous overreaction, but it dissipated soon after they stopped taking the ecdysone pills.

The researchers also found hints that the therapy could be helpful. In one of the studies, they injected the gene-plus-switch combination into 12 people with metastatic breast cancer. Each of them had already endured an average of eight previous cancer treatments, with diminishing hopes of survival. For various reasons, investigators were able to evaluate the new therapy's effect in only seven patients, however. The IL-12 treatment shrank some of their tumors, and in three people, the disease appeared to remain stable, at least for the short duration of the trial. The second safety study, in 26 patients who had been treated an average of six different times for metastatic melanoma, showed an uptick in cytokine levels and other cancer-fighting activity. In May 2015 Ziopharm initiated another study using switch-enabled IL-12 as an experimental treatment for glioblastoma multiforme, a particularly aggressive type of brain cancer.

RIBOSWITCHES

RICHARD MULLIGAN of Harvard Medical School has been working on a different kind of switch. His approach features small naturally occurring RNA molecules called ribozymes. First described in the 1980s, ribozymes are like enzymes in that they catalyze chemical reactions in the body, but most enzymes are proteins, and ribozymes consist of RNA. In a feature useful for switches, some ri-

STEPHEN J. KRASEMANN *Science Source*

SCIENTIFIC AMERICAN ONLINE Learn more about how gene switches are being combined with other experimental treatments at ScientificAmerican.com/jan2016/gene-switches

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bozymes also have the ability to cut themselves up and induce genetic molecules to which they have been attached to self-destruct.

Mulligan's constructs give rise to a ribozyme linked not to a classic gene but to a messenger RNA (mRNA) molecule. When cells make proteins, they first copy the DNA in a gene into messenger RNA (a mobile, single-stranded transcript), after which the mRNA gets translated into the protein. From the cell's point of view, the addition of a stretch of DNA or its corresponding mRNA should result in the same outcome—production of a specific protein.

As a first step, researchers assemble and inject a strand of DNA that codes for a "self-cleaving" ribozyme plus the selected therapeutic protein. If a human cell transcribed this synthetic DNA into mRNA, the ribozyme portion would cut itself, causing the rest of the mRNA molecule to appear defective; the surrounding cellular machinery would then break the mRNA apart and cause the entire process of building a protein to grind to a halt. It would be as if the gene had been turned off.

> **The ability to deliver several switch-controlled genes—each one able to be dialed up or down as needed—should make gene therapy safe and effective enough that it can become part of mainstream medicine.**

Starting in 2000, Ronald R. Breaker and his colleagues at Yale University showed how to protect the mRNA but also to turn off protein synthesis when desired. The trick was to link the ribozyme to an additional molecule called an aptamer, which is a kind of sensor that is designed to be activated by a drug. In the presence of the drug (and only in the presence of the drug), the sensor changes shape in a way that prevents the ribozyme from destroying the mRNA. With the full length of mRNA intact, the cell makes the protein. When the drug that acts on the sensor is withdrawn, the ribozyme and the mRNA self-destruct.

By 2004 Mulligan and his colleagues were regularly equipping his ribozyme switches with carefully customized drug-sensitive sensors, and he continues to hone the technology today. The sensors can be designed with great specificity, Mulligan says, further reducing the chances of unwanted side effects. As with ecdysone, the mRNA that is connected to the riboswitch would allow production of the protein only if the patient swallowed the appropriate pill. Take the pill, and you have, in effect, turned on a gene. Stop the pill, and the gene stays off.

MULTIPLE SWITCHES

ALTHOUGH SINGLE GENE SWITCHES are not yet perfected, investigators can envision a not too distant future in which multiple switches become the norm, allowing increasingly precise control of gene therapy. Combining switch-enabled gene therapy with other anticancer regimens may also bear tremendous fruit.

Already M.D. Anderson's Cooper, for example, is combining a couple of switch-enabled genes with a cell-based cancer treatment. The genes will contribute interleukin-12 and another cytokine, interleukin-15; lab tests suggest that IL-15 makes IL-12 even more effective at rallying immune cells. The third part of this experimental treatment—the cells—is a group of genetically engineered immune cells called CAR T cells that are better able to direct their firepower on cancerous tissue than naturally occurring immune cells can. Adding switch-bearing IL-12 and IL-15 genes to the CAR T cells should allow Cooper to boost the cells' potency and effectiveness. Because the gene switches and their respective activators will allow him to adjust the levels of IL-12 and IL-15 independently, he should be able to fine-tune the treatment to produce the best results with the least amount of IL-12, thereby further reducing the risk of unleashing a cytokine storm. With a touch of whimsy, Cooper calls this new suite of engineered cells "remote-control CARs."

Many technical hurdles must still be overcome, but the potential arc of progress is beginning to take shape. If inserting new genes into our bodies in the 1990s was Genetic Engineering 1.0, then the switch-based control of our genes is Genetic Engineering 2.0. Someday many of the pills that doctors give patients may be used to switch on various transferred genes at precisely the right place and time in the body instead of flooding every organ and tissue with the powerful pharmaceutical agents that act both where they are needed and elsewhere, causing side effects. Many drugs will no longer be manufactured in giant vats and so-called bioreactors in pharmaceutical facilities. Instead new gene treatments will allow patients to churn out a molecule exactly where and when it is needed most in the body. SA

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scientificamerican.com/magazine/sa

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GIANT CONVEYOR (*above*) sits idle inside the coal storage dome at the Kemper power plant in Mississippi, waiting for full operations to begin.

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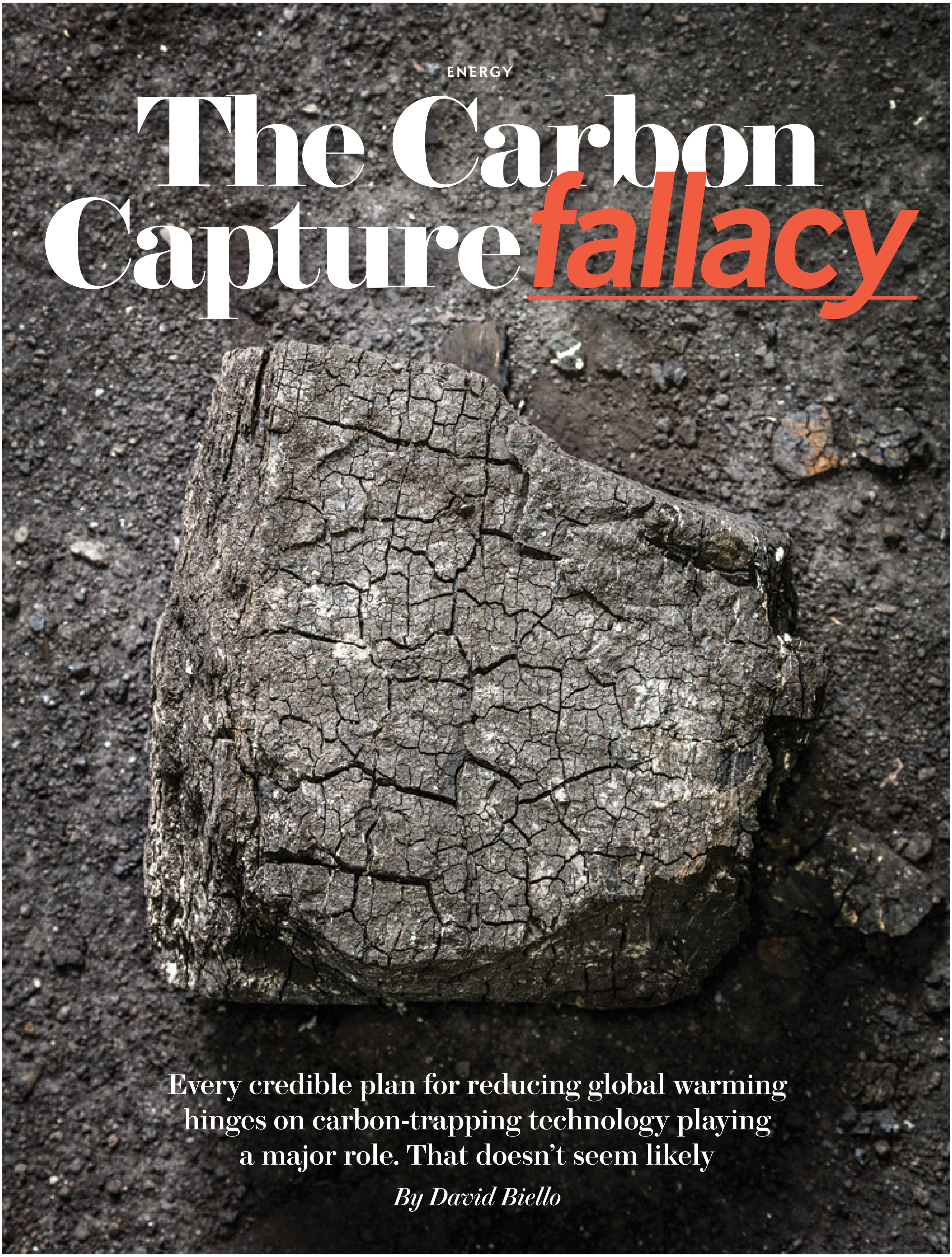
ENERGY

The Carbon Capture *fallacy*



Every credible plan for reducing global warming hinges on carbon-trapping technology playing a major role. That doesn't seem likely

By David Biello

Photographs by Jeff Wilson

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David Biello is senior reporter at *Scientific American.*

Tim Pinkston has built a massive chemistry set in the middle of a longleaf pine forest in eastern Mississippi. "I'm so happy to see it come to fruition," says Pinkston, a rangy engineer with owlish eyes, during a tour of the Kemper County Energy Facility on a warm summer morning.

Standing on a large expanse of flat land that has been clear-cut and paved with concrete, he is pointing to a vast complex of twisting, turning pipes, hundreds of miles in all, that surges skyward. At the center of this cross between a chemical factory and a power plant are two towering silos more than 300 feet tall. The twin gasifiers, each weighing 2,550 tons, can create the heat and pressure of a volcano. That is what is required to take lignite, a wet, brown coal mined from almost underneath Pinkston's feet, and turn it into gaseous fuel that is ready to burn to generate electricity.

What makes this chemistry set extraordinary is not the fuel it will soon produce but how it will handle the chief by-product: carbon dioxide, the greenhouse gas behind global warming. Rather than send the CO_2 up a smokestack and into the atmosphere, as conventional coal-fired power plants do, Pinkston and his colleagues at Kemper will capture it.

Kemper is the most advanced coal plant in the U.S. And it is key to a worldwide effort to cut back emissions of greenhouse gases, a long-awaited goal embraced by most of the more than 190 nations holding climate negotiations this month in Paris. Coal-fired power plants are the biggest source of the world's CO_2 discharges because the most polluting countries rely on them to produce a large share of their electricity. Few of those nations, including the U.S., which gets 40 percent of its power from coal, are willing to stop the burning. Without closing the plants, the only way these countries can meet their pledges is to keep CO_2 from going skyward, locking it away instead.

There is no credible plan to stave off global warming, whether from individual countries or the Intergovernmental Panel on Climate Change, that does not include such carbon capture and storage, or CCS, technology. Even the scenarios that rely heavily on nuclear power or renewable energy still require carbon capture to clean up emissions from all the neces-

IN BRIEF

Mississippi Power is building the Kemper "clean coal" power plant to generate electricity from the dirtiest form of coal and capture the resulting carbon dioxide emissions instead of sending them into the atmosphere.

Kemper will sell the CO_2 to a company that will pump it down into diminishing oil fields to force out more oil; roughly one third of the CO_2 emissions is supposed to remain trapped underground there. Burning the oil, however, would send new emissions into the sky.

Costs at Kemper and a few other similar facilities are very high, raising doubt about whether the approach is economically sustainable; to date, 33 carbon capture and storage projects have been shut down or canceled worldwide.

Without effective, affordable carbon capture, nations at this month's Paris climate talks that are committing to cut emissions will not be able to meet their pledges.

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KEMPER HAS REQUIRED 172 miles of tangled pipes, 40,000 tons of steel and two giant gasifiers (*one at center, above right*) to convert dirty coal into a cleaner-burning gas and to prevent the CO_2 by-product from being dumped into the atmosphere.

sary cement and steel. There are more than 6,000 large, industrial sources of CO_2 emissions in North America alone. About 1,000 of them are cement kilns or factories that emit 100,000 tons or more of CO_2 a year. Nearly 5,000 of them are power plants that burn fossil fuels, which emit even more. Add thousands of fossil-fuel plants in China, India and elsewhere, and they account for more than 70 percent of the planet's CO_2 pollution. It is easy to see why CCS is central to reducing this pollution.

The trouble is that carbon capture is an expensive fix. The technology itself seems to work, but the cost to build and operate a full-scale plant, which is coming to light as Kemper nears completion and other, smaller facilities gain experience, has been very high. Then there is the question of what to do with the carbon once it has been captured. Storing it deep underground in geologic formations that could hold it for thousands of years adds even more to the cost. Governments are loath to foot the bill. To recover their investments, plant owners would have to raise their customers' electricity rates far above those currently in place.

The cost of CCS has scuttled once promising efforts. A demonstration project at the Mountaineer coal plant in West Virginia buried more than one million tons of CO_2, then shut down for lack of funds to continue the experiment. In 2015 the U.S. Department of Energy canceled its hallmark FutureGen venture with industry, which was meant to rebuild an old coal plant in Illinois, after spending $1.65 billion. China has quietly changed the name of its flagship GreenGen CCS project—similar to Kemper—and is running the plant to produce power but without capturing CO_2. Only 15 CCS projects are operating worldwide today, with another seven under construction, including Kemper. All have cost billions of dollars to study, design and complete.

Kemper has found a creative way to finance its project, however. It plans to pay for CCS by siphoning off the CO_2 and selling it, an approach known as carbon capture and utilization. Some companies might use CO_2 as an ingredient in baking soda, drywall, plastics or fuel. But emissions from power plants worldwide dwarf even the raw materials that go into the more than four billion tons of cement made every year, one of the largest products that might use the gas. "With the amount of CO_2 we have to deal with, you're not going to turn everything into a valuable material," says Ah-Hyung "Alissa" Park, a chemical engineer at Columbia University, who works on this challenge.

There is one customer that could use lots of CO_2 and is wealthy enough to pay for it: Big Oil. Petroleum companies need

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vast amounts of CO_2, which they pump underground to force out oil from wells that otherwise would be running dry. Carbon capture and utilization presents a contradiction: Does it make sense, as a response to climate change, to capture carbon only to use it to obtain more fossil fuels for burning?

THE LABYRINTH

THE KEMPER PROJECT began back in 2006, in the aftermath of Hurricane Katrina, which contributed to a surge in natural gas prices. Mississippi Power was headed toward a future in which 80 percent of its electricity would be generated from natural gas, according to spokesperson Lee Youngblood. Nuclear power was too expensive, and renewable sources such as wind and solar were too intermittent. That left the local lignite. The adjacent countryside holds nearly 700 million tons of this dirtiest, wettest kind of coal—more than enough for a power plant with Kemper's capacity to burn for 50 years or more.

Conventional coal power plants typically avoid lignite because cleaning the air pollution it creates, much less the CO_2, is daunting. Pinkston and his partners realized that designing a power plant around two towering gasifiers would allow them to use the lignite and still keep pollution below federal limits. They also realized that by adding more equipment they could capture the CO_2, which made strategic sense as plans were laid; Congress was strongly considering legislation to cap greenhouse gas pollution. In 2009 the Magnolia State gave Mississippi Power permission to build Kemper, with a cost limit of $2.88 billion.

Mississippi Power's parent corporation, Southern Company, had already developed the gasifier in the 1990s as part of experiments to turn lignite into a cleaner fuel. Pinkston's team chose an industrial solvent, Selexol, to grab CO_2 from the gas created by pressurizing and heating the dirty coal. Subsequently dropping the pressure would readily release the CO_2 from the solvent, like twisting open the cap on a bottle of seltzer. The approach meant that less of the energy generated from the coal had to be devoted to cleaning up the pollution, lowering the cost. And it seemed like it all could be done with various pieces of technology that had been used in other ways for years. "There's nothing new here but the integration," says Bruce Harrington, assistant plant manager for Kemper.

Carbon capture makes for big, costly power plants, much like nuclear power. As a result, the list of dead projects is long.

That integration has proved trickier than expected. The part of the plant meant to dry the coal had to be torn down and rebuilt as a result of faulty parts. The labyrinth of pipes just kept growing as Kemper got built, stretching to 172 miles, 76 miles more than planned. Workers inside the giant tangle painted some of the machinery a special blue that turns colors if it gets too hot or cold—one of the only ways to see inside the maze to make sure everything is working properly, despite instruments at more than 30,000 points. Engineers with petrochemical expertise had to be imported, and 2,300 miles of electrical cable had

HOW IT WORKS

Carbon Capture

The Kemper power plant strings together existing technologies in a new way. Start with lignite, the dirtiest kind of coal. Convert it into gas (*1*) that is cleaner to burn (*2*) to create electricity (*3*), leaving behind carbon dioxide that can readily be captured instead of billowing up a smokestack into the air. Then use that CO_2 to extract oil from old, unproductive oil fields (*4*). Some of the CO_2 will become locked underground (*5*), so it does not reach the atmosphere and add to global warming. A handful of plants similar to Kemper have been built worldwide, but they are proving to be extremely expensive; many have been shut down or canceled because of construction delays and cost overruns.

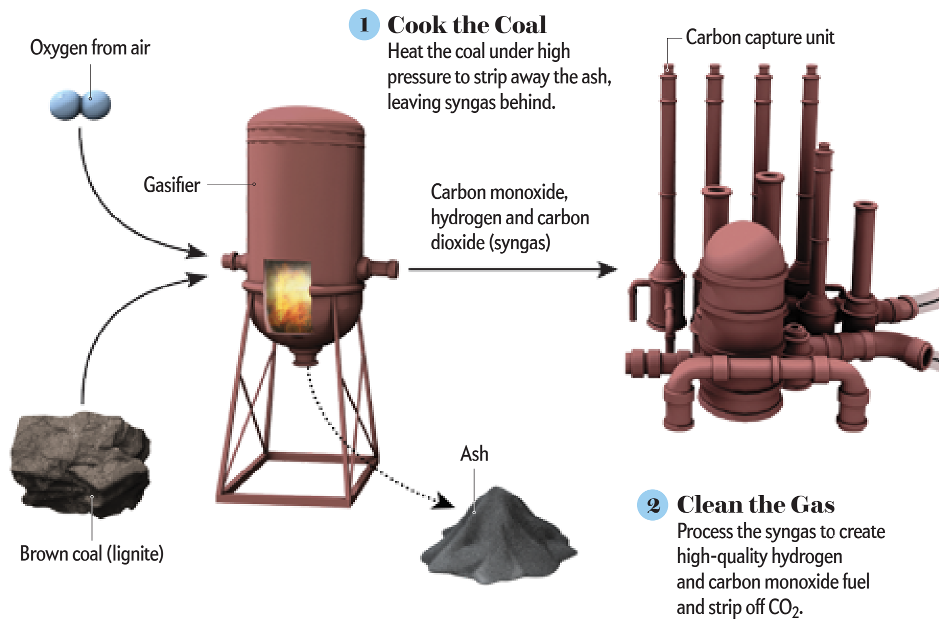

Illustration by José Miguel Mayo

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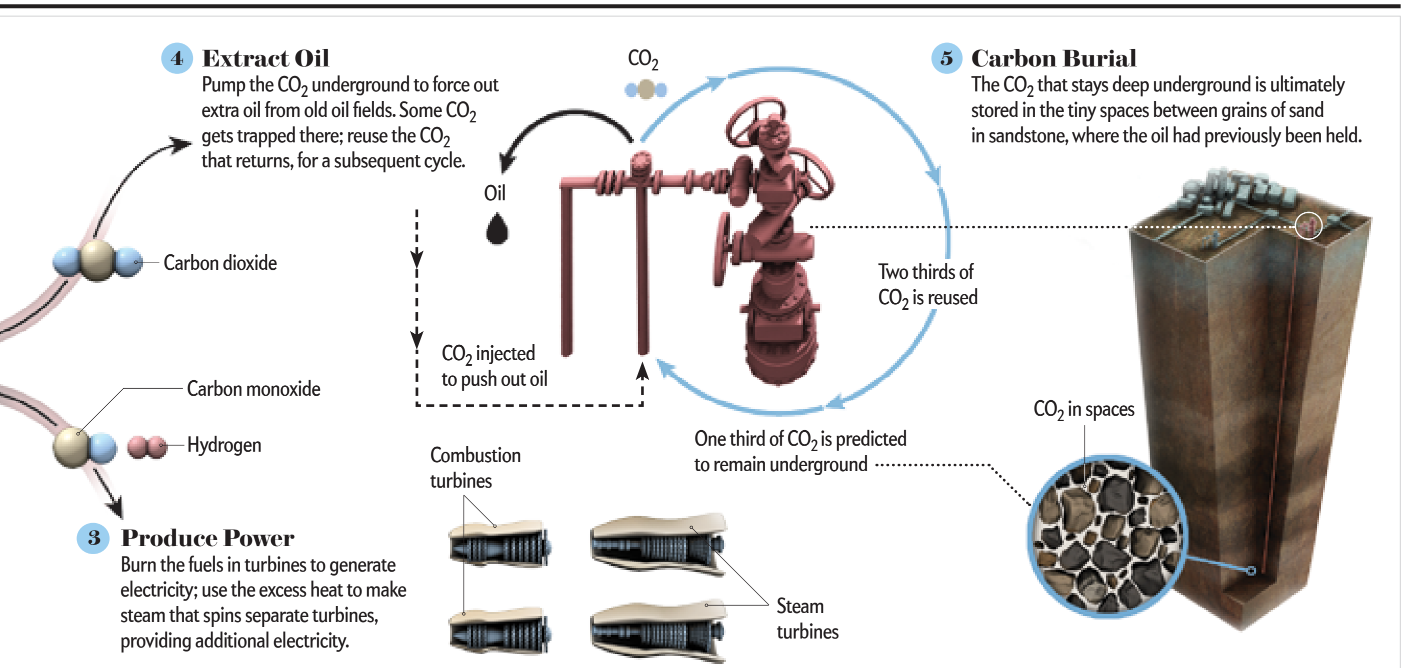
LIBERTY BELLE: The 19,000-horsepower strip-mining machine is parked on the dirt exposed after forest was clear-cut, waiting to dredge another trench to grab wet lignite coal (*right*).

to be laid, leading to a doubling of the construction workforce.

All of this complexity inflated the cost: as of October, Kemper was \$3.9 billion over budget, up from \$2.4 billion when the facility was proposed in 2009 to \$6.3 billion. Mounting delays have pushed the start date from May 2014 to at least April 2016; every month of delay costs at least \$25 million, according to Southern Company's filings to the U.S. Securities and Exchange Commission. The company had to pay back hundreds of millions of dollars in federal tax credits tied to project milestone dates that were missed.

Mississippi Power has had to turn to its own customers to avoid bankruptcy as it builds a power plant worth more than all



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the rest of the company's assets put together. In August it raised electricity rates by 18 percent. The big solution, however, is to sell pure, dry CO_2 to the oil industry.

OIL TO THE RESCUE

OIL COMPANIES have been using CO_2 to scour more oil out of the ground for decades, buying the gas from other companies that ended up drilling into underground deposits of it rather than the oil or natural gas they sought. They build a kind of mini factory atop an oil field that compresses the CO_2 and pumps it down below. The CO_2 mixes with the oil to make it flow easier and restores the pressure underground to force more oil to the surface. As much as two thirds of the CO_2 that gets pumped down returns with the oil. That CO_2 gets combined with fresh supplies and sent back down to push up yet more oil. Each cycle about one third of the gas remains underground, caught in the tiny pores in sandstone like the oil before it. That is the climate benefit—burying the greenhouse gas away from the atmosphere.

The Tinsley oil field near Kemper has produced more than 220 million barrels of oil since its discovery in 1939. Such a big field can warrant the big cost of buying CO_2 from a place like Kemper, along with added roads, truck trips and CO_2 pipelines, to force out another 100 million barrels. Denbury Resources began flooding the field with CO_2 from natural deposits in March 2008. At Tinsley, the company now recycles 670 million cubic feet of CO_2 a year and buys an additional 100 million cubic feet annually, boosting oil production from the field from 50 barrels a day to more than 5,000 barrels daily. When fully operational, Kemper plans to send roughly 60,000 million cubic feet of CO_2 a year through a new 60-mile-long pipeline to Tinsley and other fields in the region.

The catch, of course, is that when the extra oil is subsequently burned as gasoline, home heating fuel or other petroleum fuels, more CO_2 is sent into the atmosphere. The idea that combating climate change depends on a technology that uses CO_2 to produce more oil that then gets burned, producing more CO_2, reliably elicits chuckles from oil field workers.

Nationwide, the U.S. produces roughly 300,000 barrels of oil a day with CO_2, from nearly 140 fields, a number expected to double if low oil prices rebound. The DOE estimates there are 72 million barrels of oil in the U.S. (including Alaska) that could be recovered every day with CO_2. Already 5,000 miles of pipeline shuttle CO_2 from natural deposits such as the Jackson Dome in Mississippi to old oil fields, like a spider's web lurking just underground and occasionally breaking the surface with a valve or pump.

PRICEY PROPOSITION

TAPPING CO_2 in deposits currently costs about $0.50 per ton. Carbon dioxide from the complicated Kemper facility, however, may cost up to three times that.

Cost lessons are coming from several places, notably one of the first CCS projects, at the Boundary Dam power plant in Saskatchewan. In October 2014 the "clean coal" power plant began feeding power into the electric grid. SaskPower spent a little more than $1 billion to rebuild one of the plant's three coal-fired boilers to capture its CO_2 emissions. The expense worked out to about $11,000 per kilowatt of electric generating capacity, more than three times as much as a typical boiler. Mississippi Power's estimate for Kemper is similar: at least $10,000 per kilowatt.

At those levels, capturing CO_2 would add at least $0.04 per kilowatt-hour to the consumer price of electricity, according to DOE estimates. That is a 33 percent increase to the average American price of electricity: $0.12 per kilowatt-hour. Without regulations requiring carbon capture or a tax on carbon pollution that power utilities would want to avoid, the companies have little financial reason to pursue the technology. The economics are no better in China, which now consumes roughly four times as much coal as the U.S., or in India, which has declared in its submission to the Paris climate talks that it intends to build many more coal-fired power plants. The new plants are unlikely to have CCS because of the cost.

Even if the expense of carbon capture comes down, the cost of storage may also remain too high. Many of the more than 600 coal-fired power plants in the U.S. are nowhere near geologic formations that might reliably hold CO_2 that is simply pumped underground for permanent storage. Many of the power plants are also nowhere near the 1,600 U.S. oil fields that might benefit from CO_2 injection, requiring long, expensive pipelines and compressing stations. And scientists cannot say with certainty how much of a climate benefit using CO_2 to produce oil would offer. "We don't know the net amount of CO_2 stored," says Camille Petit, a chemical engineer at Imperial College London.

RECKONING DEFERRED

AS KEMPER SHOWS, carbon capture makes for big, expensive power plants, much like nuclear power. As a result, the list of defunct projects such as FutureGen is long. Worldwide, 33 CCS projects have been scrapped since 2010, according to the Global Carbon Capture and Storage Institute. Most consumed hundreds of millions of dollars before failing. Those that still exist, such as Summit Power's Texas Clean Energy Project, are struggling. Boundary Dam is having trouble meeting its own carbon capture targets.

Nevertheless, CCS projects continue because of the compelling need to combat climate change. NRG Carbon 360 is building one in Texas called Petra Nova. The utility plans to make money from selling electricity and the oil obtained by pumping 1.6 million tons of CO_2 a year into the West Ranch Oil Field near Houston. Petra Nova, scheduled to come online in late 2016 at the earliest, will capture CO_2 from only 10 percent of the power plant's total capacity, however, at a cost of $1 billion.

"Cleaning up coal plant emissions is a good goal," says Al Armendariz, a Sierra Club activist and former Environmental Protection Agency official. "But the costs of the Petra Nova project, especially compared with the low costs of renewables in Texas like wind and solar, make it questionable if CCS is the most effective way to reduce carbon emissions."

Therein lies the fallacy. Unless the U.S. starts to shut down more coal power plants and even natural gas power plants, it must find a way to convert CCS from an expensive luxury to a viable fix. Otherwise the country will not meet its long-term target of 80 percent cuts in greenhouse gas pollution by 2050.

Kemper does not provide much hope that carbon capture can be a cheap and easy solution. Two bulging stockpiles of dark coal rise beside the behemoth, baking under the Mississippi sun, waiting for the gasifiers to start up. The nine-million-pound, all-electric strip-mine machine that dug it up, renamed the Liberty

SCIENTIFIC AMERICAN ONLINE For an In-Depth Report on carbon capture and storage, see ScientificAmerican.com/jan2016/biello

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CAPTURING Kemper's CO_2 and other pollution requires the extensive labyrinth of ducts and towers shown above. The tall gasifiers that create the emissions are at the extreme left; power-producing turbines are out of view, to the right.

Belle after being imported from the U.K., sits idle. So do the big Caterpillar 789D trucks that haul the coal, which burn 28 gallons of diesel an hour, a CO_2 source not likely to be captured anytime soon.

When Kemper finally operates as designed, it will capture 65 percent of the CO_2 it would otherwise emit. It is not clean coal, just 21st-century coal, which is cleaner than its predecessors. The advanced power plant will emit formaldehyde, toluene and a long list of heavy metals, in addition to tons of acid-rain-causing sulfur dioxide, smog-forming nitrogen oxides and soot, among other forms of air pollution. It will emit 91,000 tons annually of greenhouse gases other than CO_2. There will still be toxic coal ash to deal with somehow. Ultimately Kemper will send at least 800 pounds of CO_2 into the sky for every megawatt-hour of electricity it generates. That is roughly the same as a power plant that burns natural gas, though less than half of what a typical coal-fired power plant belches.

The world stands at the threshold of finally acting to solve another garbage problem in a long list of them. Just as our forebears started paying to move trash to a landfill or to treat sewage, we will have to pay to minimize the use of the atmosphere as a dump. Kemper represents the best effort yet to clean up coal, although it is perhaps not good enough. "We would like to be making larger progress and faster progress," says Julio Friedmann, the DOE's principal deputy assistant secretary for fossil energy.

The harsh economic math shows CCS costs more than just burning coal. That may make the necessary technology impossible to develop in a world without a price on such pollution.

To generate needed revenue, Kemper has been producing electricity for more than a year now—without Pinkston's gasifiers. The turbines burn natural gas from a pipeline connected to underground deposits. None of the CO_2 exhaust is captured. It simply wafts up the smokestack, adding to the invisibly thickening blanket in the atmosphere, trapping yet more heat that Mississippi—and the rest of the world—does not need. SA

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BABY GORILLA Bokito is held by her mother, Aya, at Rotterdam Zoo in the Netherlands.

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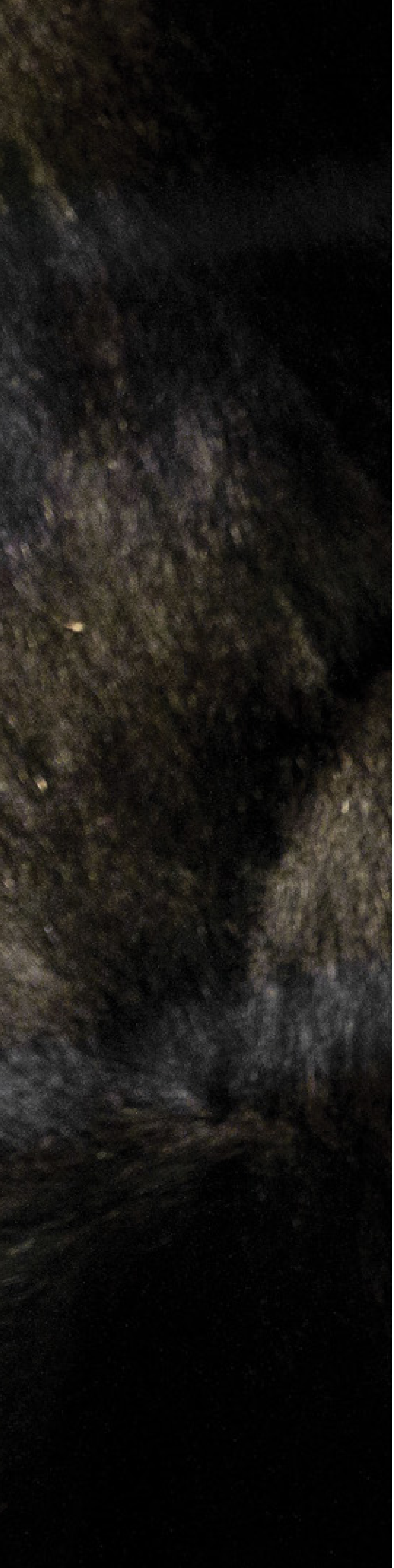

COGNITION

DO ANIMALS KNOW WHERE BABIES COME FROM

Nonhuman species can seem to comprehend procreation, but even apes lack the cognitive traits to truly understand

By Holly Dunsworth

VALERIE KUYPERS *Getty Images*

IN BRIEF

Animals often behave as though they know how babies are made.

Scientists have not studied this issue directly. But observations of how animals reason, communicate and plan imply that they lack the cognitive abilities needed to comprehend that sex produces offspring.

If our great ape cousins understood the birds and the bees, they would probably behave more like humans.

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Holly Dunsworth is an anthropologist at the University of Rhode Island. She studies ape and human evolution. Dunsworth contributes to the science blog The Mermaid's Tale and is co-writing *The Baby Makers,* which explores the evolutionary impacts of procreative beliefs.

YOU MAY KNOW KOKO AS A HUGE, HAPPY, captive gorilla who uses some sign language. She is 44 years old now. She lives in California. She likes kittens. She even understands the birds and the bees and can help plan her parenthood—or at least that's what a popular YouTube video would have us believe.

In the video, Koko's caretaker, Francine "Penny" Patterson, presents the gorilla, who is too old to give birth herself, with a notepad outlining four scenarios by which she could become a mother. A group of gorillas—one adult male, two adult females and a baby—could come live with Koko and her adult male companion, Ndume, Patterson tells Koko. Alternatively, a newborn and one or two older babies could join them; in a third scenario, just a single infant could be added. The fourth option, she explains, is that two adult females could be brought in to make babies with Ndume for Koko. Patterson hands the list to Koko, who stops scratching her chest and appears to contemplate her decision. With her right index finger, Koko taps at the last option on the notepad. "Very good idea because it would make Koko happy and it would make Ndume happy," the caretaker tells the gorilla.

So there we have it: Koko must know how babies are made. Why else would she choose baby makers over an actual baby?

It is popularly assumed that animals know all about where babies come from. In Koko's species, the sexually mature silverback males jealously guard so-called harems of females against other males. And victorious challengers often kill the infants sired by the defeated silverback before settling down to make their own. Furthermore, the gorillas avoid inbreeding between close kin by having individuals that reach reproductive age leave their family to go find a new one.

Gorillas hardly hold a monopoly on strategic sexual and parenting behaviors. Hens eject undesirable sperm before it fertilizes their eggs. Baboon dads step into the fray when their kids need social and political support. Some females holler when copulating with alpha males but not low-ranking ones—a means of advertising their attractiveness to other influential consorts. Everywhere we humans look, creatures are behaving as if they understand exactly what sex accomplishes, how they are related to potential mates as well as offspring, and how crucial it is to continue their line—with winning genes to boot. We love to narrate observations of animal sex and parenting with language that implies common ground between them and us. But do other species actually know that it is sexual intercourse that produces babies? Does Koko?

ANIMAL MINDS

IN FACT, there is no literature on whether animals understand reproduction. Scientists' best chance of finding out what animals know about how the world works comes from research conducted by primatologist Daniel Povinelli of the University of Louisiana at Lafayette on what nonhuman primates (the animals most like us cognitively) could fathom about physics and other areas involving cause and effect. In his books *Folk Physics for Apes* and *World without Weight,* Povinelli describes decades of experimental work aimed at understanding what apes know about gravity.

Some chimpanzees can be successfully trained to sort objects by the effort required to lift them. But when they are then instructed to sort objects from heavy to light without lifting them first, the chimps perform no better than by chance—evidence that their comprehension does not arise from actually thinking about weight. As Povinelli puts it, the chimps' ability stems from physical smarts, not cerebral smarts.

To comprehend unobservable phenomena such as gravity or impregnation, a creature has to be capable of abstract reasoning, the ability to mentally form representations of unseen underlying causes or forces. Humans use abstract reasoning to transfer knowledge from one situation to another, which allows us to solve problems we have never encountered before and to even invent new diversions for ourselves. Although animals such as chimpanzees are far cleverer than scientists have traditionally acknowledged, they do not appear to have this particular cognitive skill. I'm reminded of the time an astute sixth grader answered my question about "Why don't chimps play baseball?" not with their anatomical incompatibilities but with "Because you can't explain the rules to them."

Of course, just because researchers have yet to detect abstract reasoning in apes does not necessarily mean it is absent. Let us say for the sake of argument that apes do have this ability. In that case, individual apes would all still have to independently discover that sex leads to babies, or they would need to share this reproductive knowledge using some form of language. Which brings us to our next problem. Other species do not have the gift of gab.

Koko can, as a result of years of training, name hundreds of objects when prompted, but she does not engage in discussion. Without her ability to sign, you probably would not be tempted to describe Koko's native verbal communication skills as sophisticated. Gorillas grumble in the presence of large amounts of food, they grunt as they approach one another or separate from their young, they make copulatory grunts, and they chuckle when they play. Primatologists Alexander H. Harcourt and Kelly Stewart, both then at the University of California, Davis, have studied these vocalizations in mountain gorillas (which are fundamentally similar in lowland gorillas, Koko's kind) and found that they are no more complex than the threat displays gorillas make in the heat of the moment. Their utterances telegraph social status and potential near-future behavior of the vocalist, but that is all.

Indeed, limited verbal skills are the norm among wild primates. Vervet monkeys have what is perhaps the closest thing to human language, and it does not begin to measure up in its complexity. As Dorothy Cheney and Robert Seyfarth of the University

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of Pennsylvania have observed from their extensive studies of these animals in East Africa, the vervets make distinct predator alarm calls for "eagle," "snake" and "leopard." These buzzy shrieks or "words" are not learned like human words but are innate. Although the alarm calls are arbitrary, like our words, they are never used to gab about a snake they saw yesterday or to fear-monger about a leopard they may encounter tomorrow. Even if one argued convincingly that these calls are monkey words, it is difficult to get from that rudimentary "language" to one in which the speaker can explain, "When we have sex, that's what starts a baby growing."

Moreover, there is no evidence to suggest that animals have a concept of time that would allow them to link a cause such as intercourse with such a delayed effect such as a baby and to plan accordingly. Orangutans, bonobos and chimpanzees have all been observed saving tools for future use. The most sinister is Santino, a chimp at a Swedish zoo, who hoards piles of rocks under a mop of hay for tossing at visitors when they least expect it. But present observations of so-called future planning in apes are hours or a few days at most—not nearly long enough to span their gestation period, which is nearly as long as that of humans.

If animals lack the abstract reasoning, language and future planning capabilities needed to intentionally procreate, then they must know what to do (have sex) even if they do not know why (that having sex is what allows them to produce offspring and perpetuate their species). Indeed, animals may carry out all kinds of seemingly complex behaviors without actually anticipating the outcomes. Cognitive scientist Sara Shettleworth of the University of Toronto points to the example of crows that drop walnuts on hard surfaces and thereby break the nuts open. Many observers assume that the crows consciously perform this behavior with the aim of obtaining food. But a more scientific approach to understanding the nut cracking, Shettleworth notes, is to assume the cause is "proximate": the bird's internal physiological state—hunger—is linked to the presence of walnuts and hard surfaces. That is, physiology that encourages conditioned food-procurement behavior based on past success is what causes a crow to fly above hard surfaces and drop nuts, not the crow's logic about how to best satiate its hunger.

Looking to proximate causes for animal behavior is a difficult concept for humans to accept. We assume that because we know why we do things, other animals doing something similar must also know, and we anthropomorphize their behavior. But that kind of reasoning lacks the rigor needed to truly understand animal cognition.

It is more logical to explain gorilla behavior, and indeed most of the things that animals do, without attributing to them any of our powers of imagination, especially where baby making and biological paternity are concerned. Consider the silverback who kills his new consort's offspring by another male. Infanticidal silverbacks can get more of their genes into future generations of gorillas than noninfanticidal ones. So if there is any biological basis for this complex behavior or for learning it, or both, it is passed on to their sons, who may repeat their behavior, and to their daughters, who may produce sons that exhibit it. These silverbacks must display less aggression around their kin and vice versa around non-kin, and this selectivity could be aided by familiarity over time. By the time the new silverback sires infants of his own, he has lost the urge to kill them, maybe because of behavior-influencing hormones that are communicating between his body, the babies and their mothers. No aspect of this phenomenon requires any reproductive or paternity knowledge on their part.

IF THEY ONLY KNEW

IF WE COULD somehow teach our great ape cousins that sex produces babies, then we might expect their behavior in the wild to change dramatically. Males and females that wanted offspring might start collecting semen and manually inserting it. Males might also stick around longer after coitus, potentially until birth, and then remain with the baby and mother until the youngster is old enough to live independently. Females might become more competitive for mating opportunities with males they prefer. If forced to mate against their will, they might even attempt to abort the pregnancy. Females who wanted to avoid pregnancy might hide themselves away during their estrous period, when they are fertile and attract the most male attention.

Knowing where babies come from would lead to an understanding of how individuals are related, which would have its own behavioral consequences. Both males and females might begin to take an interest in the reproductive behavior of their mature offspring and perhaps start positioning their family in the society when offspring are still immature so as to help them eventually land an elite mate. They might even prevent youngsters from leaving the group at reproductive maturity so they could better influence their reproductive lives. Brothers and sisters, knowing they come from the same parents, might also form tighter and more enduring relationships than they are known to do in these species. Aware of their relationship to offspring that mate with individuals in other groups and produce babies of their own, apes would probably show decreased competition and violence between groups that might have normally been enemies but are now understood to be blood-affiliated.

In other words, if apes comprehended that sex leads to babies, they would act a lot more like people. Which brings us back to Koko. I didn't just watch that one film of Koko. I watched many others, and in so doing I noticed that Koko practices her signs and learns new ones by exposure to symbols on a notepad. It seems that each time a symbol is presented to her she taps it with her finger first, whether she can recall and perform the correct sign or not. Koko's motherhood choice, then, did nothing to demonstrate that she understood the question, let alone baby making.

No matter how passionate or nurturing it is, nothing about the sexual, social and parental behavior of animals requires knowledge of reproduction. In contrast, much about *Homo sapiens* behavior does. Somewhere along the line, our species developed cultures rich in beliefs about procreation, family and connectedness—beliefs that in many ways set us apart from our ape cousins and indeed every other creature on the planet. SA

MORE TO EXPLORE

Folk Physics for Apes. Daniel J. Povinelli. Oxford University Press, 2000.
World without Weight. Daniel J. Povinelli. Oxford University Press, 2012.

FROM OUR ARCHIVES

The Social Genius of Animals. Katherine Harmon; *Scientific American Mind,* November/December 2012.

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Clara Moskowitz is a senior editor at *Scientific American.*

MATHEMATICS

Elegant Equations

Mathematicians often see more than cold logic in symbols and numbers. They see the sublime

By Clara Moskowitz

ARE EQUATIONS BEAUTIFUL? TO SCIENTISTS, FORMULAS' ABILITY TO represent fundamental truths or concisely capture complexity is indeed exquisite. To many in the public, though, they can be the opposite of beautiful—intimidating, utilitarian and opaque. Yet for others, the very mystery can be alluring: even when we cannot understand what equations say, we can be moved by knowing they have meanings beyond our comprehension. And mathematicians and nonmathematicians alike can be drawn in by the purely aesthetic appeal of these expressions, whose graceful and sometimes inscrutable symbols combine in visually satisfying ways.

To explore both the inherent and visual beauty of math, mathematician Daniel Rockmore of Dartmouth College teamed up with Bob Feldman of Parasol Press, which publishes fine art prints. They asked 10 famous mathematicians and physicists to write out what they conceived of as the "most beautiful mathematical expression" and had the print shop Harlan & Weaver turn the responses into 22-by-30-inch etchings called aquatints. "I was careful to not give any instruction beyond that sentence," Rockmore says. "As the 10 prints show, it means different things to different people."

Many picked classic equations, such as the famous formula by Isaac Newton that was Stephen Smale's choice (*page 73*). Others selected expressions closer to home, including equations they discovered themselves that are deeply tied to their lifelong research interests—for example, the MacDonald equation chosen by Freeman Dyson (*page 72*). "I love Dyson's," Rockmore says. "It's thin, and it's sleek; visually, it's so sharp. And with those little exclamation points for the factorials, it's beautiful."

The project is called Concinnitas, after the word used by Italian Renaissance scholar Leon Battista Alberti to describe the balance of elements necessary for beautiful art. The collection premiered in December 2014 at the Annemarie Verna Gallery in Zurich and has since been shown at five more galleries, with plans to travel elsewhere in the coming months. Here we show five of the prints. SA

IN BRIEF

A group of famous mathematicians and physicists were asked to identify the "most beautiful mathematical expressions" they knew to display as aquatint prints.

The collection, called Concinnitas, after an Italian Renaissance expression for balanced beauty, probes the connection between mathematics and art.

Some participants chose equations they discovered themselves; others picked classics that have long inspired them. Some formulas correspond to physical laws, whereas others are pure abstractions. Five are featured here.

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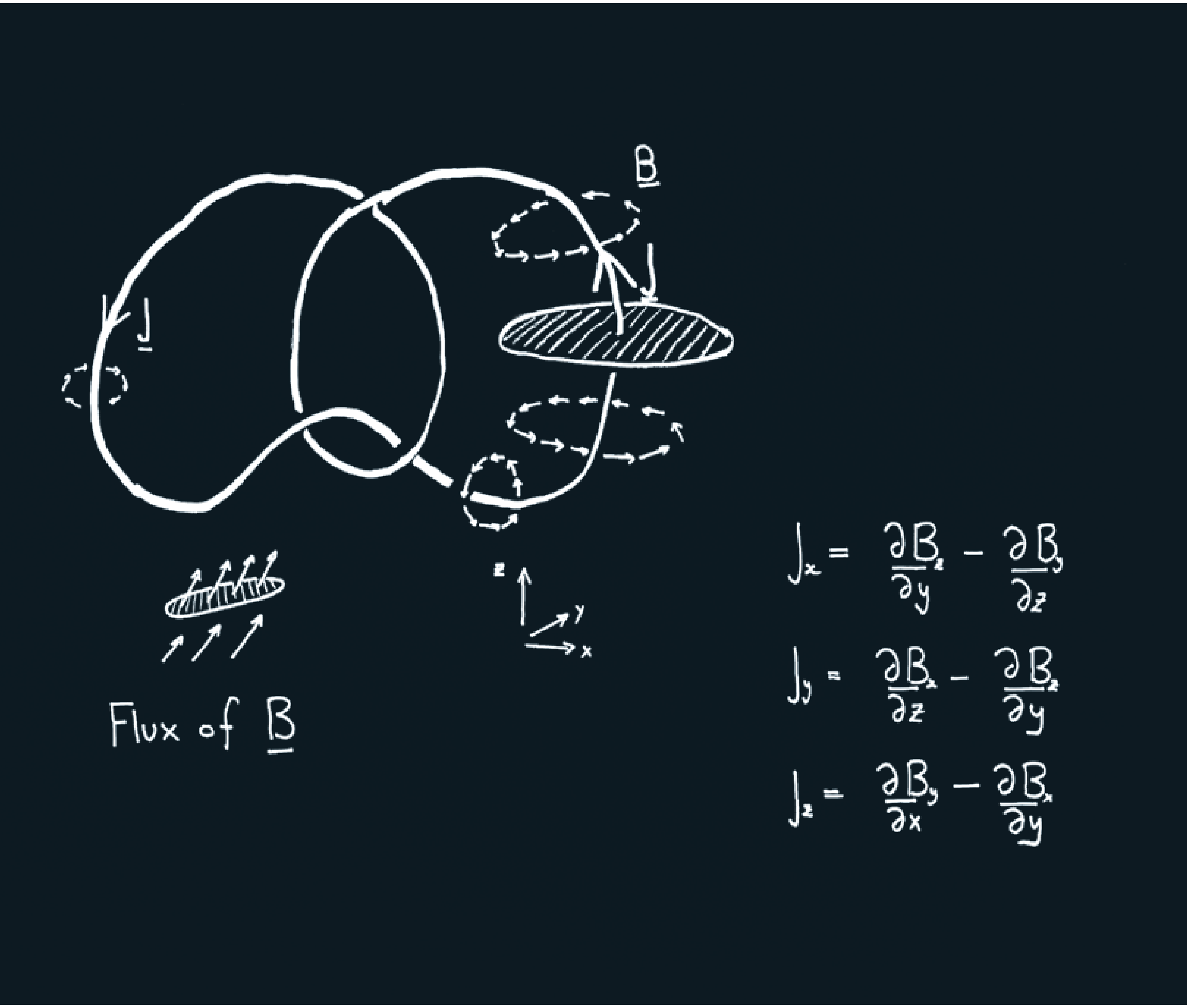

Ampère's Law

Chosen by Simon Donaldson, Stony Brook University

Instead of selecting a single equation, Donaldson listed three and drew a picture of a wire tied in a knot. The current (*J*) running through the wire toward the large arrows creates a magnetic field (*B*) in the direction indicated with small arrows. The three equations are Ampère's law, which describes how a current generates a magnetic field. Together the image and the equations represent the connection between electromagnetism and topology—the branch of mathematics concerned with knots and spatial relations. Donaldson says he finds beauty in revealing such "new connections between things that one previously thought of as quite different." For example, by applying some of the ideas and mathematics of electromagnetism to the study of knots, researchers have found new ways to determine whether different knots are fundamentally the same, the way a doughnut and a coffee mug are essentially the same shape deformed to look different.

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MacDonald Equation

Chosen by Freeman Dyson, Institute for Advanced Study, Princeton, N.J.

Dyson derived this equation—a reformulation of a classic called the tau function, famously studied by Indian mathematician Srinivasa Ramanujan—shortly after another mathematician, Ian MacDonald, independently arrived at it. In it, five variables—*a, b, c, d* and *e*—are subtracted from one another in 10 combinations. The differences are multiplied together and divided by the product of the factorials for 1, 2, 3 and 4 (for example, 4 factorial, expressed as $4! = 1 \times 2 \times 3 \times 4$). The elegance of this formulation appeals to Dyson because it reveals a kind of symmetry, or balance, among the five variables in the tau function. The equation is also beautiful in a more indefinable way, he says. "It doesn't particularly tell you anything true about the universe—it just stands for itself, like a piece of music," he notes. "Asking what it means is rather like asking what a Beethoven trio means. You just have to listen to it." The equation belongs to the branch of pure mathematics called number theory.

$$\tau(n) = \sum \frac{(a-b)(a-c)(a-d)(a-e)(b-c)(b-d)(b-e)(c-d)(c-e)(d-e)}{1!\,2!\,3!\,4!}$$

Moduli Space of Curves of Genus *g*

Chosen by David Mumford, Brown University

$$\mathcal{O}_{\mathcal{M}_g}(K) \cong \left(\Lambda^{g} \pi_* \omega_{\mathcal{C}_g/\mathcal{M}_g}\right)^{\otimes 13}$$

Our universe has just three dimensions of space, but mathematicians can imagine it containing many more. This equation describes a space with dimensions numbering $3g - g$ and shows that if g is large enough, the shape of the space is negatively curved, like the surface of a saddle. When Mumford discovered the formula, he recalls, "I thought it was a startling result, especially that strange number 13 that came up." Most fundamental mathematical expressions consist only of variables, operators and small whole numbers such as 1 and 2, making the relatively large quantity 13 in this equation an aberration. To Mumford, the strangeness of the equation makes it beautiful. "As a mathematician, you feel you're discovering these logically determined facts—they have to be this way and no other way," he says. "And suddenly you come up with a strange number, and you think, 'Why did it have to be *this* way?' "

COURTESY OF PARASOL PRESS (*all equation images*)

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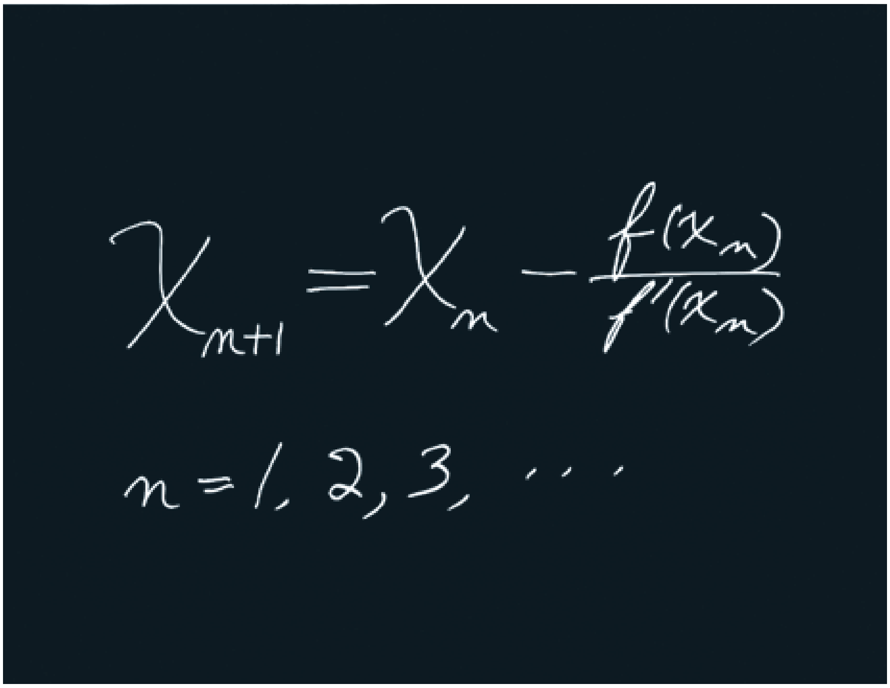
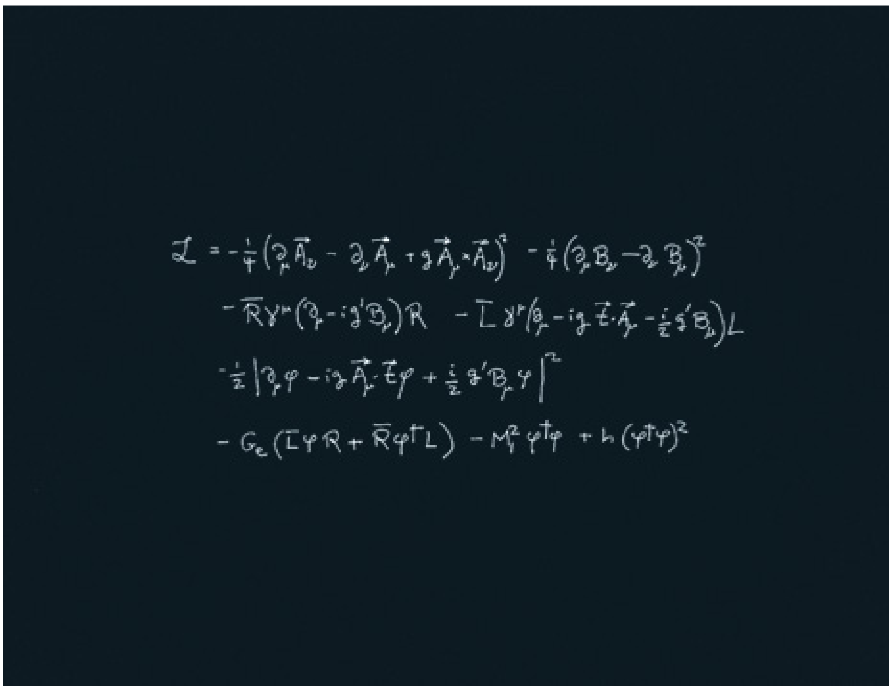


Newton's Method

Chosen by Stephen Smale, City University of Hong Kong

A mathematical trick, known as Newton's method, approximates the solution to an equation—$f(x)$—whose exact answer cannot be calculated, such as the square root of 2 (which is the irrational number 1.4142 ...). It works by starting with any real number, x, and subtracting the function $f(x)$ divided by the derivative of that function, $f'(x)$, to get a new x. Every time this process repeats, x gets closer and closer to an estimation of the solution. The method is very handy, yet even Newton lacked a good theory for why it works. That mystery is what makes this equation so appealing to Smale. "So much of my work is devoted to understanding Newton's equation—under what conditions it works," he says. "My own feeling is that a great problem is never solved; it just becomes the focus of more and more work."



The Lagrangian of the Electroweak Theory

Chosen by Steven Weinberg, University of Texas at Austin

Two of nature's four fundamental forces—electromagnetism and the weak force (responsible for radioactive decay)—unite in this equation, revealing themselves to be two sides of a single coin. The formula, which Weinberg devised in 1967, established that at certain energies, electromagnetism and the weak force act as one, the "electroweak" force—a discovery that later won him the Nobel Prize in Physics. Here the $\mathcal{L}$ represents the Lagrangian density, essentially the energy density of the fields associated with the force, which are denoted by A and B. "I think the shape of the symbols on the page has nothing to do with its beauty," Weinberg says. "It is the fact that the theory is rigid, that it can't be changed without screwing it up, that makes the theory beautiful. Its details are fixed by some underlying fundamental principle."

MORE TO EXPLORE

Math Is Beautiful, But Is It Art? Jen Christiansen in ScientificAmerican.com SA Visual blog. Published online January 27, 2015. http://blogs.scientificamerican.com/sa-visual/math-is-beautiful-but-is-it-art

Mathematics and Art: A Cultural History. Lynn Gamwell. Princeton University Press, 2015.

Full set of Concinnitas prints: www.concinnitasproject.org

FROM OUR ARCHIVES

The Mass of the Photon. Alfred Scharff Goldhaber and Michael Martin Nieto; May 1976.

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MORE TO EXPLORE
FOR MORE BOOK RECOMMENDATIONS, VISIT
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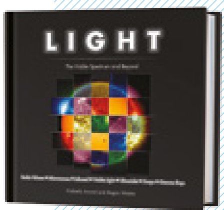
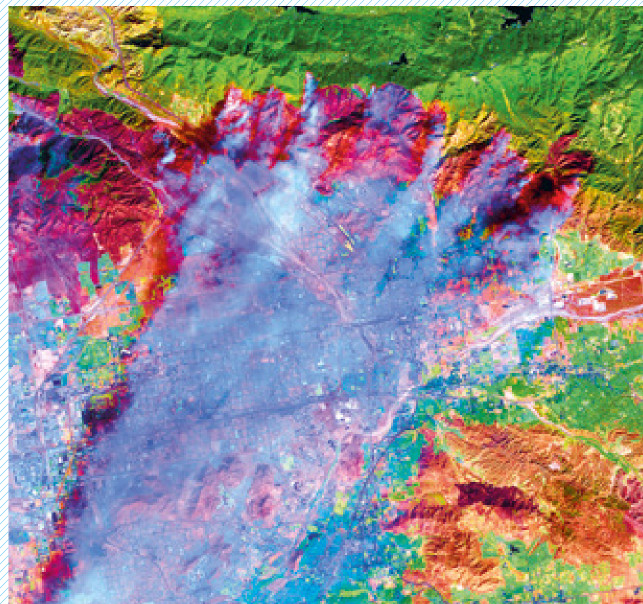
Light: The Visible Spectrum and Beyond

by Kimberly Arcand and Megan Watzke. Black Dog & Leventhal Publishers, 2015 ($29.99)



Light is all around us in more ways than we think, present not just in visible rays but in the microwaves that often transmit wireless Internet and the x-rays that expose the health of our teeth and bones. This large-format book provides a visual introduction to the entire electromagnetic spectrum, illustrating each wavelength band with captivating photographs taken through telescopes, microscopes and cameras sensitive to all ranges of light. The book also illuminates fascinating quirks of light—such as the fact that reindeer can see in the ultraviolet range and that gamma rays kill cancer cells—that illustrate how central it is to life.

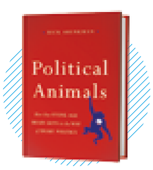


An image of wildfires in California reveals active areas (*bright red*) and burn scars (*darker red*) in infrared and visible light.

NASA/ASTER SATELLITE

Political Animals: How Our Stone-Age Brain Gets in the Way of Smart Politics

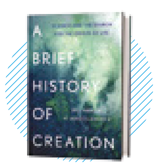
by Rick Shenkman. Basic Books, 2016 ($26.99)



In this presidential election year, historian and journalist Shenkman offers a timely look into psychological patterns that drive political behavior. He describes how irrelevant events such as shark attacks, droughts and sports outcomes can stimulate instincts that change how we vote. Football fans whose teams win, for example, are more likely to support incumbent candidates. Shenkman details, in particular, four ways that people behave irrationally when it comes to politics: we become apathetic about our government, we incorrectly size up our leaders, we punish politicians who tell hard truths and we fail to apply empathy to political decisions. "Though politics is usually framed in terms of the résumés, ideology, and personality of the candidates, it's not really about them," he writes. "It's about us and what's going on in our brain."

A Brief History of Creation: Science and the Search for the Origin of Life

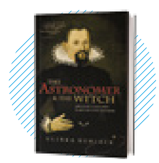
by Bill Mesler and H. James Cleaves II. W. W. Norton, 2015 ($27.95)



No scientific quandary is as confounding, controversial or important as the question of how life began, argue journalist Mesler and geochemist Cleaves. "It touches upon not only how we came to be, but *why* we came to be," they write. "It is, in a sense, the ultimate question." Here the authors chronicle the historical quest to understand how life arose from nonlife, from Aristotle's theory of the "spontaneous generation" of life, to Charles Darwin's 19th-century musing on the origin occurring "in some warm little pond," to the latest modern-day research on the "LUCA," or last universal common ancestor. They find that the scientific understanding of life itself has advanced considerably over the years but that the fundamental event that began it some four billion years ago is just as much a mystery as it ever has been.

The Astronomer and the Witch: Johannes Kepler's Fight for His Mother

by Ulinka Rublack. Oxford University Press, 2015 ($29.95)



Johannes Kepler was a renowned 17th-century German astronomer, mathematician, natural philosopher … and lawyer? Although he is not known for the last occupation, in 1620 he put his work on hold, packed up his household and moved back home to Württemberg, Germany, to defend his mother in court on charges of witchcraft. Historian Rublack uses the facts of the case to explore the intellectual, political and religious turmoil going on at that time in Europe, as well as the complexities of Kepler's own beliefs, which encompassed both scientific rationalism alongside the possibility of magic: while maintaining that witches did exist, he insisted that there was no evidence his mother was one. This surprising chapter in Kepler's life offers a window to better understand the famous genius and the world that created him.

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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

Murder in the Cave

Did *Homo naledi* behave more like *Homo homicidensis?*

By Michael Shermer

“Fossil First: Ancient Human Relative May Have Buried Its Dead” (Reuters). “Why Did *Homo naledi* Bury Its Dead?” (NOVA Next). These are just two of the many hyped headlines that appeared last September in response to a paper purporting the discovery, in a cave in South Africa, of a new species by paleoanthropologist Lee R. Berger of the University of the Witwatersrand, Johannesburg. There were reasons for skepticism from the get-go.

The age of the fossils is undetermined, so it is impossible to conclude where in the hominin lineage the fossils fit. Their hands, wrists and feet are similar to small modern humans, and their brain volume is closer to that of the small-brained australopithecines, like Lucy, so it is not clear whether this combination constitutes a new species or a variation on an existing species. Instead of publishing in *Science* or *Nature,* the prestigious journals in which major new fossil human finds are typically announced, the authors unveiled their discovery in eLIFE (elifesciences.org/content/4/e09561), an open-access online journal that fast-tracks the peer-review process. And instead of meticulously sorting through the 1,550 fossils (belonging to at least 15 individuals) for many years, as is common in paleoanthropology, the analysis was published a mere year and a half after their discovery in November 2013 and March 2014.

What triggered my skepticism, however, was the scientists’ conjecture that the site represents an example of “deliberate body disposal,” which, as the media read between the lines, implies an intentional burial procedure. This, they concluded was the likeliest explanation compared with four other hypotheses.

Occupation. There is no debris in the chamber, which is so dark that habitation would have required artificial light, for which there is no evidence, and the cave is nearly inaccessible and appears never to have had easy access. *Water transport.* Caves that have been inundated show sedimentological layers of coarse-grained material, which is lacking in the Dinaledi Chamber, where the specimens were uncovered. *Predators.* There are no signs of predation on the skeletal remains and no fossils from predators. *Death trap.* The sedimentary remains indicate that the fossils were deposited over a span of time, so that rules out a single calamitous event, and the near unreachability of the chamber makes attritional individual entry and death unlikely.

Finally, the ages of the 13 individuals so identified—three infants, three young juveniles, one old juvenile, one subadult, four young adults and one old adult—are unlike those of other cave deposits for which cause of death and deposition have been determined. It’s a riddle, wrapped in sediment, inside a grotto.

I believe the authors are downplaying an all too common cause of death in our ancestors—homicide in the form of war, murder or sacrifice. Lawrence H. Keeley, in *War Before Civilization* (1996), and Steven A. LeBlanc, in *Constant Battles* (2003), review hundreds of archaeological studies showing that significant percentages of ancestral people died violently. In his 2011 book *The Better Angels of Our Nature,* Steven Pinker aggregates a data set of 21 archaeological sites to show a violent death rate of about 15 percent. In a 2013 paper in the journal *Science,* Douglas P. Fry and Patrik Söderberg dispute the theory that war was prevalent in ancient humans by claiming that of the 148 episodes of violence in 21 mobile foraging bands, more than half “were perpetrated by lone individuals, and almost two-thirds resulted from accidents, interfamilial disputes, within-group executions, or interpersonal motives such as competition over a particular woman.”

Whatever you call it—war or murder—it is violent death nonetheless, and further examination of the *Homo naledi* fossils should consider violence (war or murder for the adults, sacrifice for the juveniles) as a plausible cause of death and deposition in the cave. Recall that after 5,000-year-old Ötzi the Iceman was discovered in a melting glacier in the Ötztal Alps in the Tyrol in 1991, it took a decade before archaeologists determined that he died violently, after he killed at least two other people in what appears to have been a clash between hunting parties. It’s a side of our nature we are reluctant to admit, but consider it we must when confronted with dead bodies in dark places. SA

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COMMENT ON THIS ARTICLE AT
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Illustration by Izhar Cohen

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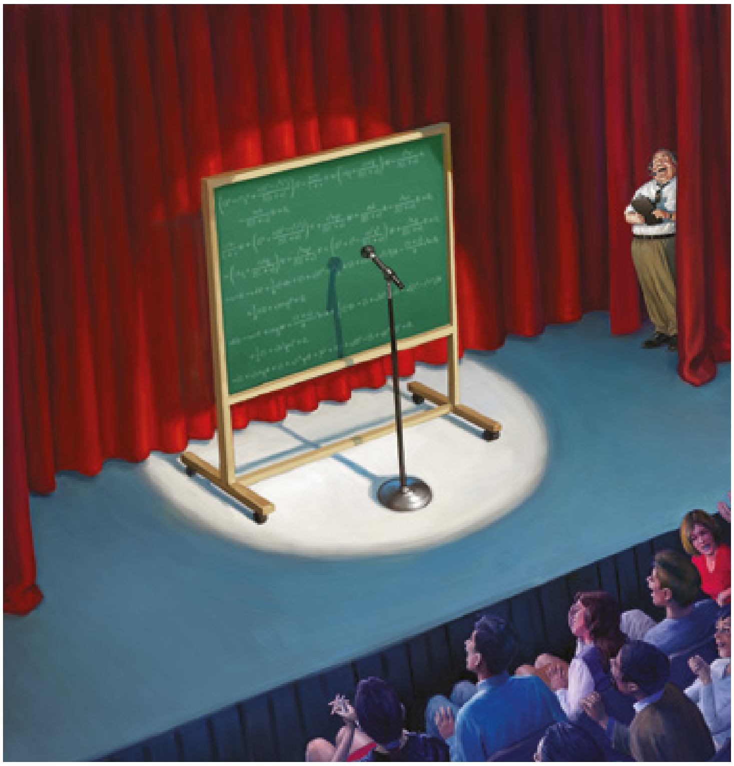
Steve Mirsky has been writing the Anti Gravity column since a typical tectonic plate was about 35 inches from its current location. He also hosts the *Scientific American* podcast Science Talk.



3*x* Equals an Omelet

Math can be fun for readers of all *h*'s

By Steve Mirsky

Before he ever took a formal algebra class, Arthur Benjamin got a lesson he never forgot. The future mathematician's father said, "Son, doing algebra is just like arithmetic, except you substitute letters for numbers. For example, $2x + 3x = 5x$ and $3y + 6y = 9y$. You got it?" The young Arthur replied that he grasped the concept. After which his dad said, "Okay, then what is *5Q + 5Q?*" Arthur replied "10*Q*." And his father said, "You're welcome!"

That terrible, wonderful gag appears early in Benjamin's new book, *The Magic of Math: Solving for x and Figuring Out Why.* Benjamin is now a professor at the small and prestigious Harvey Mudd College in Claremont, Calif. If your alma mater's name is Mudd, chances are you're a scientist, engineer or mathematician—the school specializes in those fields.

The occasional stabs at humor in Benjamin's book will leave the reader figuratively bloodied but unbowed and buoyed in the brainpan. Whether it's been decades since you last took algebra or you're currently dealing with the aches of solving for *x, The Magic of Math* is a good read. Even though it includes, gasp, equations.

For example (and don't bother to try to stop me if you've heard this one), consider a pizza pie to be a very short cylinder. The volume of a cylinder equals *pi* times the radius squared times the height. That is, $V = pi\ r\ r\ h$. And so, deep breath, for a pizza of radius z and height a, $V = pi\ z\ z\ a$. And if you think that exercise was too cheesy, you need a thicker crust.

"I want people not just to learn mathematics, I want people to love mathematics," Benjamin told me when he visited New York City in September. "That's what Martin Gardner's writing did for me." Gardner was the longtime writer of the famous Mathematical Games columns for *Scientific American,* inspiring many young Arthurs to describe their round tables as fulfilling the requirement that $x^2 + y^2 = r^2$. Before tests, these individuals might cram a lot. (Sorry, I've been inspired by Arthur's father to embrace the dark side of the forced jokes.)

One of my favorite parts of the book considers a rope tied to the bottoms of the two goalposts on opposite ends of an American football field, 120 yards away from each other. That's 100 yards plus the two 10-yard butt-slapping and dance areas—I mean the end zones. The taut rope is thus 360 feet long as it traverses the grass along the centerline of the field. Now imagine that the rope gains a measly little foot, so that it's now 361 feet long. At the 50-yard line, how high could you lift the rope, while leaving its ends on the ground at the goalposts?

Feel free to stop reading for a moment if you want to do the relatively simple calculation. (Or for any other reason—I am not the boss of you.)

By lifting the rope, you create an imaginary triangle with a base of 360 feet, an as yet unknown height of h feet, and two sides of 180.5 feet, half of the 361-foot-long rope. Now drop an imaginary plumb line from the top of the rope, and the big triangle can be divided into two smaller and equal *right* triangles, each with a hypotenuse of 180.5 feet and sides of 180 feet and h feet. Perform the primordial Pythagorean prestidigitation (the sum of the squares of the two sides of a right triangle equals the square of the hypotenuse), and you'll find that the one-foot-longer rope can be lifted high enough for even the most gigantic lineman to trundle under, more than 13 feet off the ground.

I'm fond of this example because the result just felt wrong to me. How could a single additional foot of slack have such a large effect? And yet the math is indisputable, as math tends to be. *The Magic of Math* thus reminds the reader that reality cares not how you feel about it. Which is why I recommend the book to anyone involved in making public policy. No amount of additional analysis, fact-finding commissions, committee hearings or white papers will change the height of that rope. 10*Q*. 10*Q* very much. SA

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Illustration by Matt Collins

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PROMOTION

The Agenda Setters

Bringing Science to Life

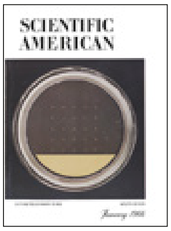
Photos by Andrew Federman

Google Science Fair 2015

Googleplex | Mountain View, CA | September 21, 2015

To encourage the next generation of science enthusiasts, SCIENTIFIC AMERICAN has been a key partner of the global Google Science Fair competition since it launched in 2011. Each year, Editor in Chief Mariette DiChristina heads up the judging team. This year we also awarded the SCIENTIFIC AMERICAN Innovator Award to honor a project in the pure sciences. The $25,000 award went to Krtin Nithiyanandam (pictured bottom center) for developing a molecular 'Trojan Horse' for the earlier, minimally-invasive diagnosis of Alzheimer's Disease.

At this year's event at the Google campus in California, we and the other Google Science Fair partners – LEGO Education, National Geographic and Virgin Galactic –hosted science activities for thousands of children and their families.



January 1966

Communication by Laser

"The announcement in 1960 that a working model of a laser had been achieved was greeted with enthusiasm by workers in many fields. Since the light produced by a laser is both coherent and monochromatic, it was felt at the time that the laser was the answer to a communication engineer's prayer. Although a practical, working system of long-distance communication by laser has yet to be built, the initial enthusiasm has not waned."

Japanese Discovered the New World?

"As New World civilizations have become better known archaeologically, striking parallels have been observed with the architecture, religious practices and art styles of Asia. It has been suggested that these parallels are evidence of unrecorded 'discoveries' of America long before Columbus. Most professional archaeologists have remained unconvinced because the possibility of an independent origin of the parallel traits could not be eliminated. Recent archaeological investigations on the coast of Ecuador, however, lead to only one conclusion: a boatload of inadvertent voyagers from Japan strayed ashore in the New World some 4,500 years before Cortes reached Mexico.—Betty J. Meggers and Clifford Evans"

January 1916

A National Highway

"I took my annual vacation this year in the form of a trip by automobile to the Pacific Coast over the Lincoln Highway [built in 1913]. Two years ago, when I made this same trip, I was doing something out of the ordinary, one of perhaps 50 tourists who took the same journey. This spring I do not believe it an exaggeration to state that I was but one out of 5,000 who essayed to reach the Pacific Coast by motor, and did reach it after a series of experiences which would make the writer of the modern popular thriller blush with shame for his lack of imagination. It is the best road, the only road, leading from the Atlantic to the Pacific."

Some sections of the Lincoln Highway remained unpaved until the 1930s.

Faster Motorcars

"The most interesting mechanical development of the year has been the growth in popularity of the multi-cylinder car, as represented by the twin-four and the twin-six, the former mounting an eight-cylinder and the latter a twelve-cylinder engine. The advantages of the multi-cylinder car are so fully dwelt upon elsewhere, that they need no elaboration; it is sufficient to mention the constant and even torque, the absence of vibration, the great flexibility of control and the rapidity of the acceleration [*see illustration*]."

For more on the leading edge of motor vehicle technology in 1916, see www.ScientificAmerican.com/jan2016/automobiles

1916: Motorcars had become popular, dependable and increasingly used for the sport of racing on purpose-built speedways.

January 1866

Great Comet of 1861

"M. [Emmanuel] Liais, the celebrated astronomer, submitted elaborate calculations proving beyond question that on the 19th of June, 1861, the earth really did pass through one of the comet's tails. The moment of contact was twelve minutes past six A.M., Rio Janeiro time, and, according to the calculation of its dimensions made by M. Liais, the earth must have been wholly immersed in the tail for about four hours! This immersion in the tail of a comet had no perceptible influence upon the weather, a very remarkable fact, adding one more to the many reasons there were already for supposing that cometary matter is some million of times rarer than our atmosphere."

In 1880 Heinrich Kreutz calculated the orbital period of the comet to be 409 years.

Manias

"Strange passions seize upon mankind at times. Coins have their value, pictures are eagerly bought up, Dutch tulips command monstrous prices, and lately postage stamps have claimed attention. All these freaks of human nature are taken advantage of by shrewd individuals of a speculative turn of mind who desire to turn a penny, honest or otherwise. Some French engravers have thought it worth their while to design a series of novel postage stamps, the like of which were never seen before. These stamps were represented to be the issue of the 'Sandwich Islands' post-office, and as such were eagerly bought by confiding purchasers who probably supposed that nothing was too absurd for that region. The Hawaiian stamps, not genuine, are orange, violet, green, and other colors of the rainbow."

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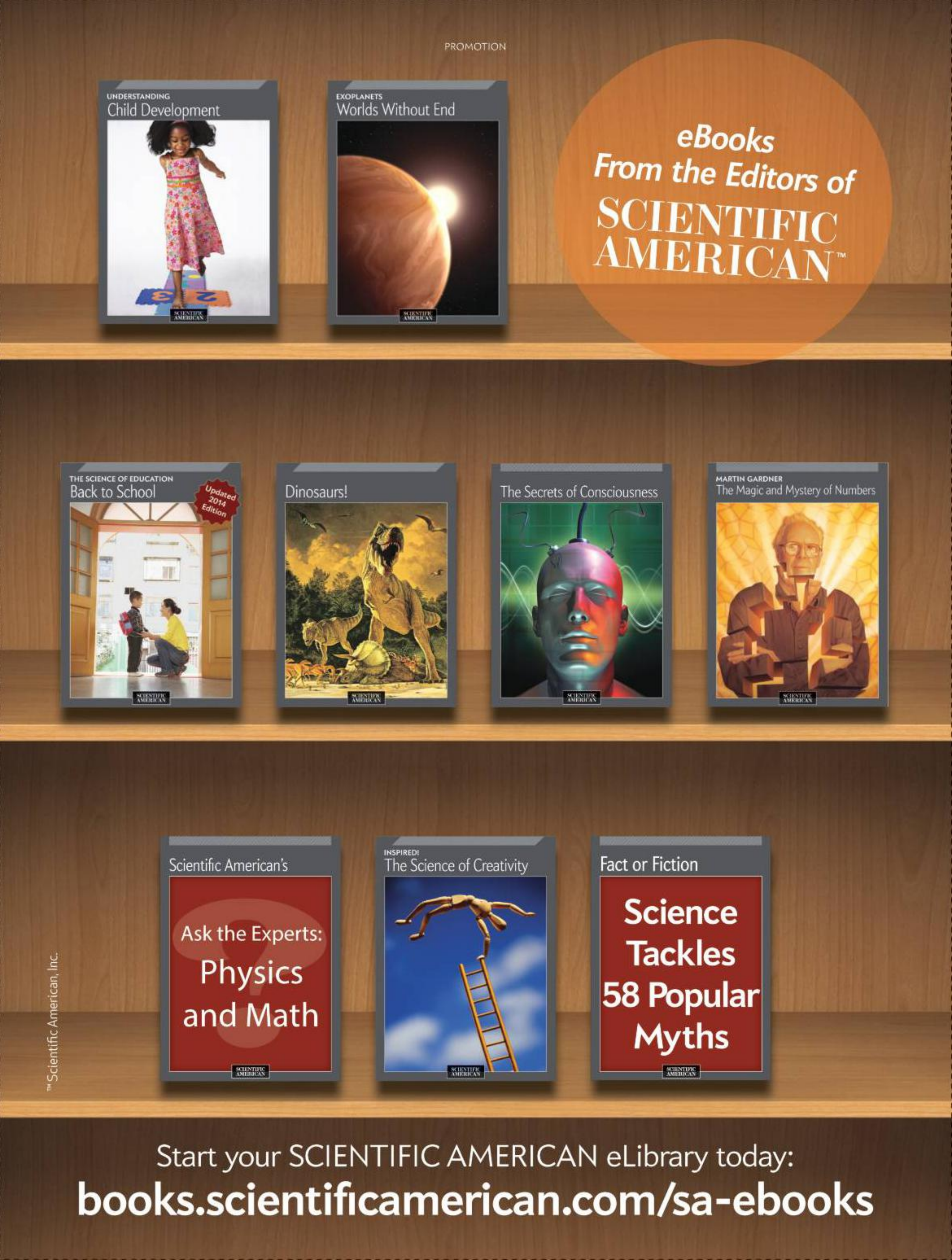
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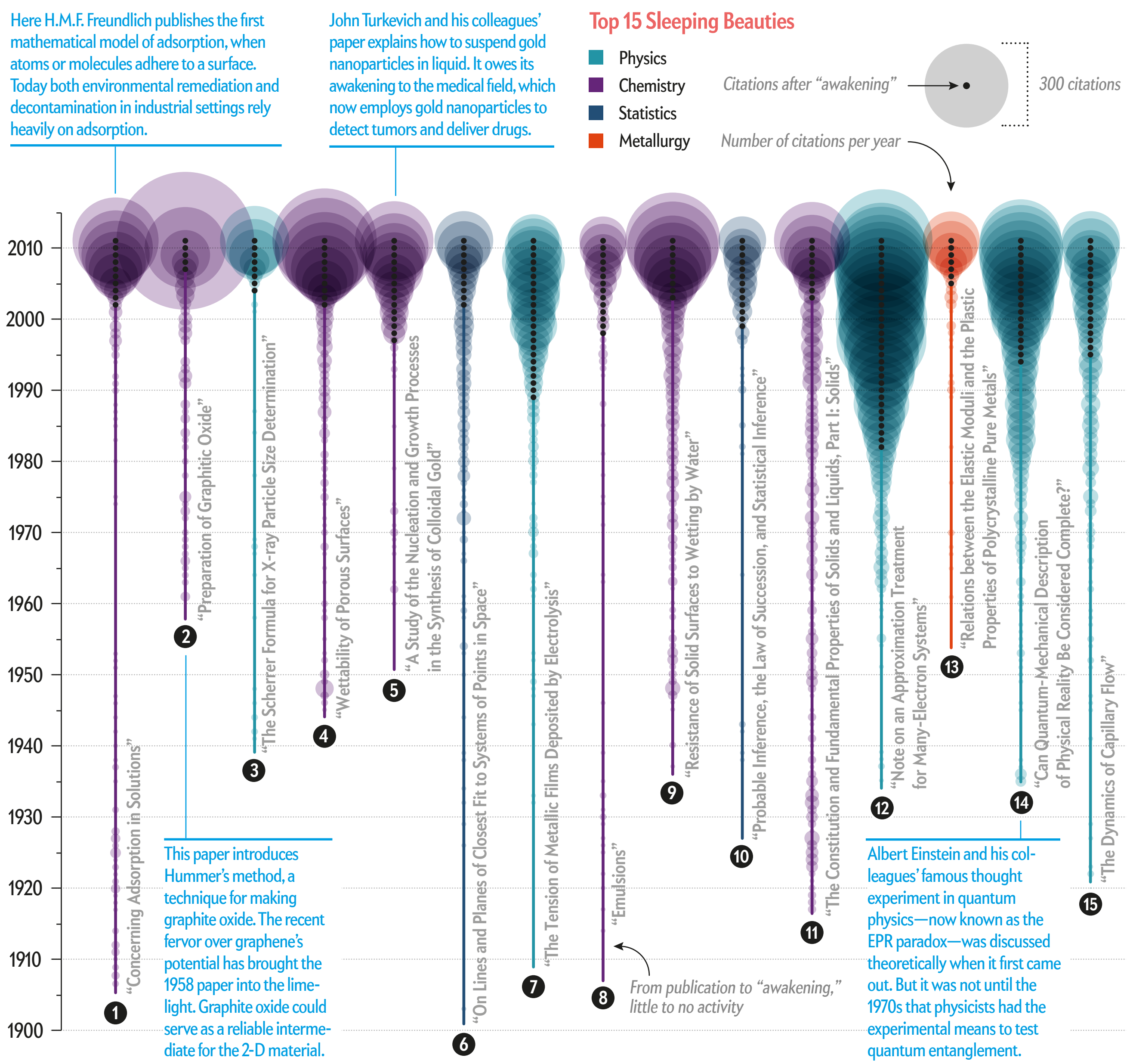
Sleeping Beauties of Science

Some of the best research can slumber for years

Discovery lies at the core of science, but rediscovery can be just as important. Indiana University Bloomington researchers recently combed through 22 million scientific papers published over the past century and found, to their surprise, dozens of “Sleeping Beauties”—studies that sat dormant for years and then suddenly got noticed. The top finds—the ones that languished in obscurity the longest and later got the most intense attention from the scientific community—came from chemistry, physics and statistics. What tended to wake up these sleeping findings? Scientists from other disciplines, such as the medical field, in search of fresh insights, as well as the ability to test once theoretical postulations. Qing Ke, a graduate student in informatics who worked on the project, says that most likely Sleeping Beauties will become even more common in the future because of the increasing availability and accessibility of scientific literature. —*Amber Williams*



SOURCE: “DEFINING AND IDENTIFYING SLEEPING BEAUTIES IN SCIENCE,” BY QING KE ET AL., IN *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES USA,* VOL. 112, NO. 24; JUNE 16, 2015

Graphic by Tiffany Farrant-Gonzalez

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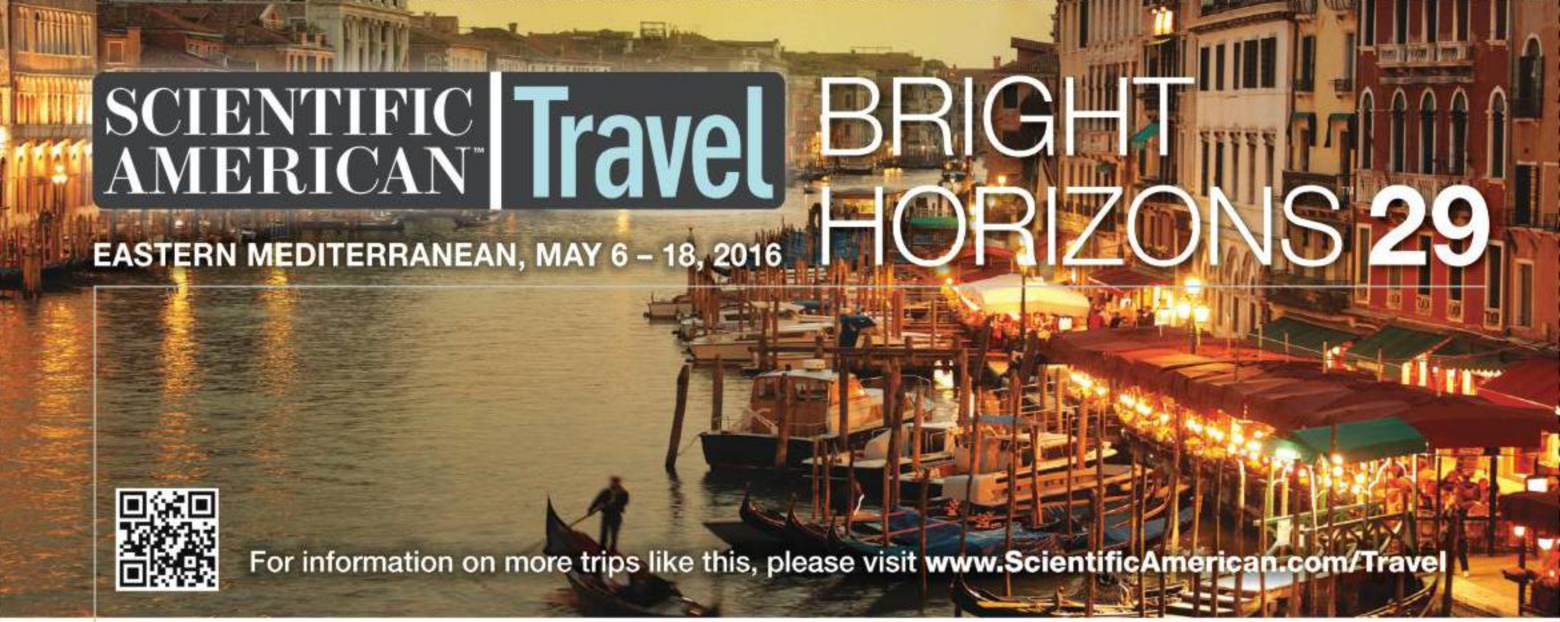

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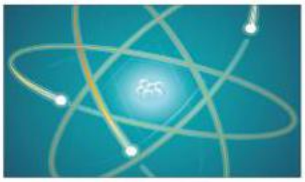

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