SPACE
In Search of Alien Jupiters

EDUCATION
Building the 21st-Century Learner

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AUGUST 2015

HOW WE CONQUERED THE PLANET

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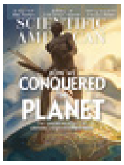

In the millions of years over which the human family has been evolving, many human species have walked the planet. But only one, *Homo sapiens,* managed to spread across the whole world. Two unique innovations—extreme cooperation and projectile weaponry—allowed our kind to dominate, according to a new hypothesis. Illustration by Jon Foster.

SCIENTIFIC AMERICAN

August 2015 Volume 313, Number 2

COURTESY OF G. BRAMMER/EUROPEAN SOUTHERN OBSERVATORY *(Very Large Telescope)*

FEATURES

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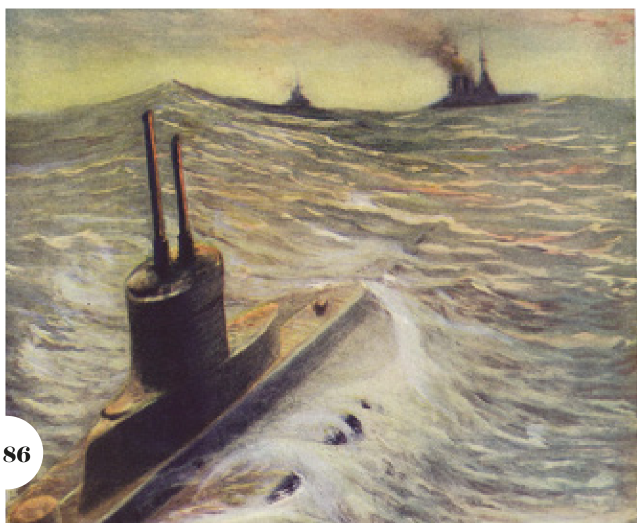

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DEPARTMENTS

ON THE WEB

Maternal Mortality
Scientific American investigates the reasons behind a sharp increase in pregnancy-related deaths among U.S. women over the past few decades.
Go to www.ScientificAmerican.com/aug2015/maternal-mortality

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

Happy 170th!

On Thursday, August 28, 1845, as the innovations born of the industrial revolution were sweeping across the young U.S., an aspirational weekly broadsheet with handsome engraved illustrations appeared, promising to be "The Advocate of Industry and Enterprise, and Journal of Mechanical and Other Improvements": *Scientific American*. Its founder and editor, an itinerant inventor and landscape painter named Rufus Porter, promised informational graphics about "*New Inventions, Scientific Principles,* and *Curious Works*" and news of "progress of Mechanical and other *Scientific Improvements,*" including patents, "Miscellaneous Intelligence" and even poetry. (The first issue had a tribute to "Attraction," with rhymes that somehow managed to range from fundamental physical forces such as gravity to the lure of human romance.)

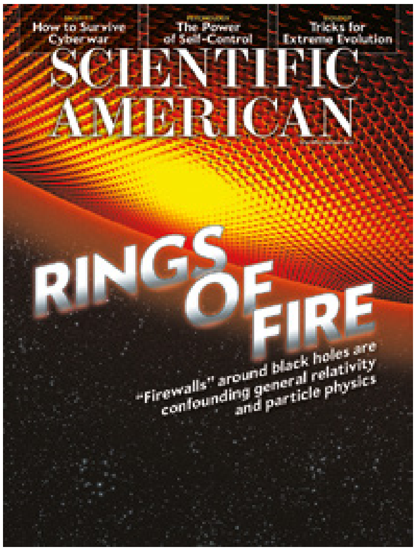
Today *Scientific American* is our country's longest continuously published magazine—the flagship of editions in 15 languages (there are another eight of its sister title, *Scientific American Mind*)—with all the modern iterations you would expect: a lively Web site with daily news and blogs, apps, newsletters, a book imprint with Farrar, Straus and Giroux, a textbook series with Macmillan Higher Education, eBooks, events, and more. The magazine has grown up alongside its parent country, documenting the scientific advances and technological innovations that have enhanced human lives and fueled economic growth.

Starting this month, we're celebrating our 170th anniversary with a series of editorial activities that will run through the end of the year, and we invite you to participate. Stay tuned.

Scientific American readers have curious minds and a shared passion for lifelong learning. In the inaugural issue, Porter noted that the editors would foster student development. "As a family newspaper," he wrote in his introduction, "it will convey more useful intelligence to children and young people, than five times its cost in school instruction." (At the time, that cost was $2 annually, worth more than $60 in 2015 dollars.) Today, with national concerns about educating our next generation to succeed in science, technology, engineering and mathematics (STEM), we still report on these topics. (See our special section on "Building the 21st-Century Learner," starting on page 54.) And I deeply hope, as a lovely 1911 editorial in this magazine put it, that we may continue to inspire with tales that evoke "the inherent charm and fascination of science." SA

Illustration by Nick Higgins

editors@sciam.com



April 2015

BLACK HOLE FIREWALLS

In "Burning Rings of Fire," Joseph Polchinski explains that according to Stephen Hawking's theory of black holes, when a matter-antimatter pair of particles comes into existence just outside a black hole, one of those particles could go into the hole and the other could be radiated out, which would eventually deplete the hole's entire mass.

Wouldn't it be random whether the antimatter particle or the matter particle of the pair fell into the black hole? If so, then over time, the amount of matter in the black hole annihilated by infalling antimatter particles from spontaneously generated matter-antimatter pairs should be balanced by an equal number of infalling matter particles from such pairs. Therefore, matter-antimatter particle pair formation just outside the horizon of a black hole should have no effect on the hole's mass.

Byron Bowman
via e-mail

POLCHINSKI REPLIES: Bowman is correct that black holes produce particles and antiparticles in equal numbers. This led Hawking to predict that if a black hole formed from a star made of matter, it would end up converting half of that matter to antimatter. But antimatter still has positive mass and energy, so that part of the story does not change.

"If businesses want to change the equation in relation to STEM education, then their investment is part of that equation."

DAVID L. HARDIE
BENTLEY, WESTERN AUSTRALIA

CYBERSECURITY

Keren Elazari's prescriptions for cybersecurity in "How to Survive Cyberwar" emphasize individual users taking steps to protect themselves. But if the goal is to ensure that each person is a cybersecurity expert, we've already lost the war.

Individuals do not have the market power to "demand that companies make their products more secure," as Elazari suggests. Large companies must be regulated to ensure that private data are not stored unencrypted and easy to access. Each corporate security breach should be followed up by large punitive damages. Every time Microsoft allows malware to hijack my browser, I should be able to file for, and receive, a token payment of a few dollars.

Chuck Simmons
Redwood City, Calif.

ADDICTION VS. SELF-CONTROL

In his article on self-control, "Conquer Yourself, Conquer the World," Roy F. Baumeister makes a statement about a study on addiction that indicates to me that he has had little experience with what people typically refer to as physical dependence: "The frequently recurring nature of these urges is what makes quitting a challenge. But the addict is not beset by the mythically insurmountable difficulty of resisting an overwhelming desire."

I hope that he is not referring to the situation addicts are in when withdrawal symptoms crescendo. Nicotine in particular will drive the dependent's executive processes into retreat. Eventually there comes a crisis point. The "grab a smoke" and the "make this stop" situations are completely different. Try not eating for a few days; it's in the same ballpark.

Ken Adams
Cary, N.C.

ABDICATING TRAINING

In arguing for a DARPA-like approach toward funding educational efforts in "The Case for Education Moon Shots" [Forum], Russell Shilling of the U.S. Department of Education cites a study in which "97 percent of the CEOs of major American companies identified a lack of science, technology, engineering and math (STEM) skills among the national workforce as a problem for their businesses."

As a lifelong educator (now involved in human resources consultancy within the field), I am sick and tired of business organizations advocating for higher-quality outputs from the education sector but wanting someone else (that is, the government) to make the investment. Even though many of these organizations will continually argue for less government intervention on a range of issues, they turn into a socialist collective when it comes to education and training.

No sustainable business model will deliver a dividend without investment. If businesses want to the change the equation in relation to STEM education, then their investment is part of that equation.

David L. Hardie
Bentley, Western Australia

DRIVERLESS CARS

Each time I read about the progress of driverless cars in articles in your magazine such as "Driverless Tech Inches Ahead," by Corinne Iozzio [Advances], I wish I could take the design teams on a tour of the roads around where I live in southeastern Pennsylvania. Some of the roads are so poorly maintained that there are no lane markings anymore.

During the past two winters, there have been huge potholes, with drivers weaving to avoid the worst ones. Are the new driverless cars going to have real-time pothole evaluation and avoidance? And when plows pile snow up at the edge of roads, it is often not clear where the curb is.

Maybe these cars will be sold only in states that meet a certain level of infrastructure maintenance, but if the design

teams want to work in real-world, worst-case conditions, they need to pack up their tent and move their cozy operations away from the West Coast and join us here in the Northeast!

Andrew Benton
Blue Bell, Pa.

VACCINATION IS A PRIVILEGE

I agree with Steve Mirsky's conclusion in his Anti Gravity column on antivaccine sentiments among parents and politicians ["Immune Reaction"]: it is important for children to be immunized against disease.

It is interesting to look at the developing world, where parents are begging for this opportunity and willing to walk miles to make sure their children get vaccinated. Fortunately, Gavi, the Vaccine Alliance, was recently fully funded to immunize 300 million children in the developing world by 2020, which will save five million to six million lives. Of course, donors such as the U.S. must keep their pledges to ensure this happens.

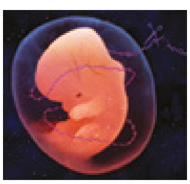
Willie Dickerson
Snohomish, Wash.

CLARIFICATION

"Atom Smasher Amps Up," by Clara Moskowitz [Advances], includes a photograph of a resistive sextuple magnet as part of an article about the Large Hadron Collider at CERN near Geneva. The device, which was being tested at CERN, is not part of the LHC.

ERRATA

"A Flare for Cancer," by Joshua A. Krisch [Future of Medicine 2015], incorrectly states that spheres have more surface area than other shapes.



The illustrations for "Why Embryos Should Not Be Off-Limits" [Science Agenda, July 2015] and "Star Wars," by Michael West [Forum, July 2015], were miscredited. The correct artists are Skip Sterling (*top*) and Steven Hughes (*bottom*).

LETTERS TO THE EDITOR

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Letters may be edited for length and clarity. We regret that we cannot answer each one. Post a comment on any article at ScientificAmerican.com/aug2015

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Docs, Glocks and Stray Bullets

Laws that stop physicians from discussing gun safety with patients are bad for public health

We complain, in the U.S., that our doctors don't know us: office visits last only a few minutes, conversations are curt and high-tech testing takes the place of talking. Now, perversely, one state has passed a law expressly forbidding doctors from asking certain questions about patients' health and lifestyle.

The questions concern guns and gun safety. This year the U.S. Court of Appeals for the Eleventh Circuit has been hearing arguments about a Florida statute that says doctors cannot ask a patient about gun ownership—including safety issues and children's access—unless they believe such information is relevant to the patient's medical care. If the law is upheld, doctors will not be able to talk to patients about one of the biggest threats to public health in the U.S.—guns were involved in slightly more than 11,000 homicides, 21,000 suicides and 500 accidental deaths in 2013, according to the U.S. Centers for Disease Control and Prevention. To wall off this topic from doctor-patient conversations is a dangerous step.

Gun ownership is a right protected, of course, by the Second Amendment to the U.S. Constitution. In 2011 Governor Rick Scott of Florida and the state's legislature felt that that right was being infringed on by Florida doctors. Scott signed the Privacy of Firearms Owners bill, which said that patients could file a complaint with the state if they felt doctors were being too nosy. Robert Young, a physician representing a group called Doctors for Responsible Gun Ownership that supported the bill, explained the rationale: "Too many Floridians had bad experiences with physicians telling them to get rid of their guns, when many patients who own and use guns knew that wasn't right." He added that "many gun owners also fear the creation of databases of gun ownership because that could be a step toward confiscation someday."

Florida doctors countered that the law deprived them of their own constitutional right, the First Amendment guarantee of free speech, and that deprivation prevented them from helping patients. They sued, backed by the American Medical Association and other physician groups. The First Amendment is important here: one judge who heard this case noted that courts have repeatedly said that free and open doctor-patient communication is crucial to care and the common good. (The judge also noted that Florida lawmakers relied on anecdotes in crafting the law rather than on data or studies.)

Physicians are supposed to offer counseling not just about diet and exercise but also about injury prevention connected to boating, bicycling and riding motorcycles, observed Stuart Himmelstein, then head of the Florida Chapter of the American College of Physicians, in a lawsuit document. Counseling a motorcyclist to wear a helmet is no different than counseling a gun owner to store firearms safely. Safe behavior with guns will have a health effect beyond the gun owner: 89 percent of accidental firearms-related injuries to children happen in homes, often when a youngster grabs an unattended and loaded weapon, according to a study published in *JAMA Pediatrics* in 1996.

Concerns about doctors creating a database of gun owners are also misguided. Doctors already are explicitly prohibited from keeping records on gun ownership by a provision of the federal Affordable Care Act.

The lawsuit about the Florida statute, which has been dubbed "Docs vs. Glocks," has bounced among various courts in recent years, with some judges upholding the law and some overturning it. Meanwhile Indiana and Texas have been considering their own versions this spring. The Eleventh Circuit should follow the evidence and strike down the Florida law this year, an action that could keep other lawmakers from getting between patients and their doctors.

Nobody wants to tread on gun owners' constitutional rights. But the Second Amendment does not protect them or innocent bystanders from bullets. SA

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Illustration by Thomas Fuchs

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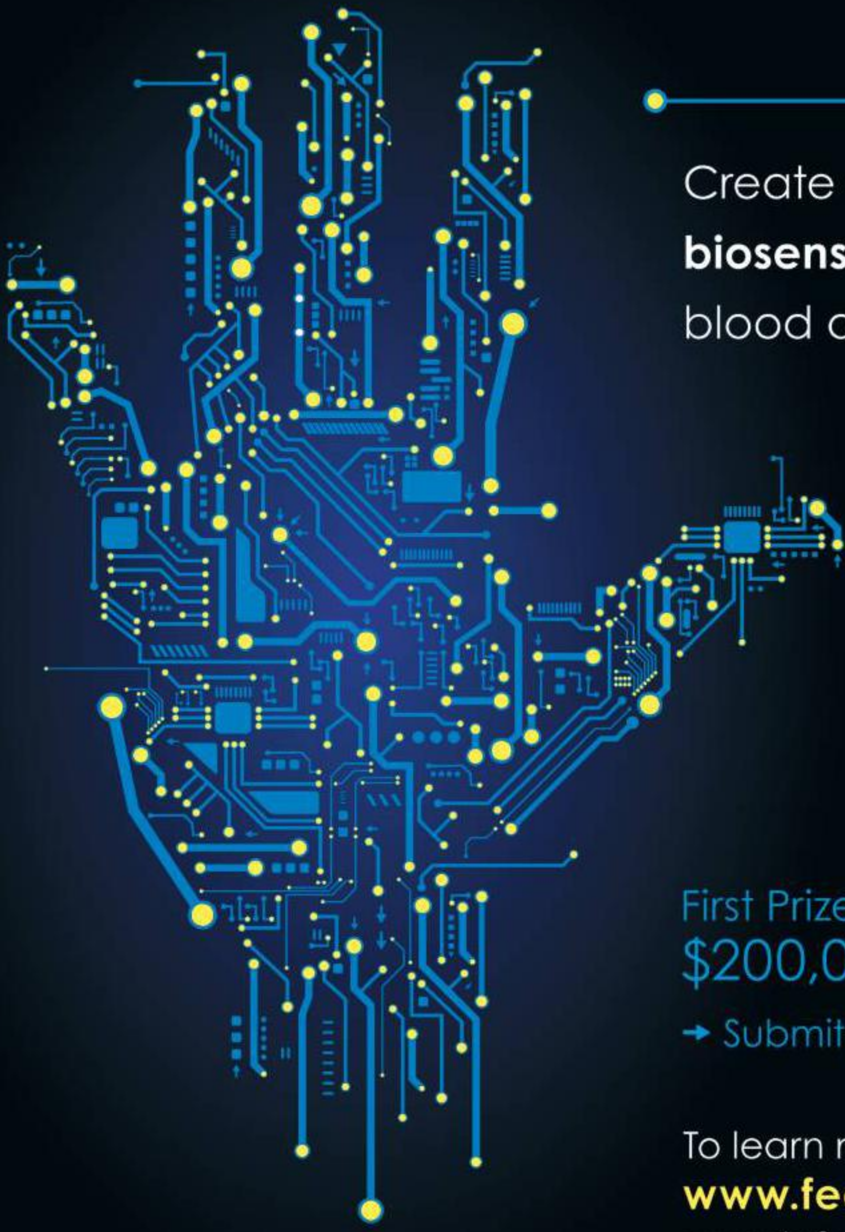

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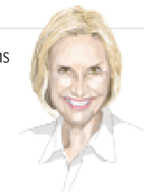
Linda Billings, Ph.D., is a science communications researcher based in Washington, D.C. She has written about the history of astrobiology, human spaceflight and NASA's public affairs operations. She blogs at http://doctorlinda.wordpress.com



Space Cowboys

How jingoism corrupts American rhetoric on human spaceflight

Throughout the history of the U.S. human spaceflight program, a peculiarly American rhetoric of manifest destiny, frontier conquest and exploitation has dominated official and public discourse. Take, for example, the credo of the Space Frontier Foundation, an American nonprofit advocacy group "dedicated to opening the Space Frontier to human settlement as rapidly as possible … creating a freer and more prosperous life for each generation by using the unlimited energy and material resources of space." Such rhetoric reveals an ideology of human spaceflight—a set of beliefs about the nation's right to expand its boundaries, colonize other lands and exploit their resources.

This ideology rests on a number of assumptions about the role of the U.S. in the global community and American national character. According to this ideology, the U.S. is and must remain "number one" in the world community, playing the role of political, economic, scientific, technological and moral leader, spreading democratic capitalism. The metaphor of the frontier, with its associated images of pioneering, homesteading, claim staking and taming, looms large in this belief system.

The rhetoric of human spaceflight advances a conception of outer space as a place of wide-open spaces and limitless resources—a space frontier. From John F. Kennedy to Barack Obama, U.S. presidents have embraced this rhetoric of frontier conquest and exploitation. So have NASA administrators, members of Congress and decades of expert panels.

I have heard a White House official tout a concept for large-scale industrialization of the moon as "a phenomenally inspiring long-term vision" for the U.S. space program. The invitation-only Pioneering Space National Summit, held in February in Washington, D.C., yielded a declaration that "the long-term goal of the human spaceflight and exploration program of the United States is to expand permanent human presence beyond low-Earth orbit and to do so in a way that will enable human settlement and a thriving space economy." One of the groups that participated in this summit, the Tea Party in Space, advocates "applying the core principles of fiscal responsibility, limited government, and free markets to the rapid and permanent expansion of American civilization into the space frontier."

Rhetoric matters. More than 30 years of my own observations, along with results from public opinion surveys over at least as many years, indicate that the community of American human exploration advocates is predominantly white and male. The rhetoric of frontier conquest and exploitation may appeal to this demographic, but I doubt it has much allure more broadly. Women constitute half of the world's population. A majority of people on Earth are not American, or European, or "white." In my many years of critiquing the American rhetoric of manifest destiny, non-Americans have repeatedly told me that they are baffled, if not offended, by this rhetoric.

Other spacefaring nations take a more pragmatic approach to plans for space. In his foreword to the *European Space Directory 2015,* European Space Agency director general Jean-Jacques Dordain wrote that the aim of his agency is to "maintain its role as one of the world-leading space institutions, addressing its key relationships with its partners and its efficiency." The Japan Aerospace Exploration Agency's slogan is "explore to realize," expressing "our philosophy of becoming an agency of realizing a safe and affluent society."

At a time when the U.S. needs to be building sustainable partnerships with other nations to continue exploring space, "USA, Number One!" is not a good way to start productive conversations. In a 2012 paper Jacques Blamont, a founding director of the French space agency CNES, argued that people are losing interest in the human exploration of space "because spacefaring nations, and especially the USA, have clung on to outmoded cold war ways of thinking about it. The US attitude of 'command' over its international partners will no longer work." It is time for human spaceflight space advocates to reexamine their rhetoric—to think about what these words mean to the vast variety of people who are not American, not white, not male, and not interested in moving to Mars. SA

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Illustration by Ross MacDonald

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Earthquakes in the Himalayas (*Nepal, top row*) could fracture dams and lead to disaster scenarios like those seen in the Indian town of Kedarnath, when monsoon rains in 2013 caused a lake to burst its borders (*bottom row*).

LORENZO MOSCIA *Redux Pictures (top left)*; BULENT DORUK *Getty Images (top right)*; GETTY IMAGES *(bottom left)*; CORBIS *(bottom right)*

GEOLOGY

The Impending Dam Disaster in the Himalayan Mountains

Two of the most populous nations—China and India—are building hundreds of dams in a violently active geologic zone

Earlier this year earthquakes in Nepal leveled thousands of buildings, killed upward of 8,500 people and injured hundreds of thousands more. The magnitude 7.8 and 7.3 temblors also cracked or damaged several hydropower projects, underscoring another imminent danger: dam bursts. More than 600 large dams have been built or are in some stage of construction or planning in the geologically active Himalayan Mountains, but many are probably not designed to withstand the worst earthquakes that could hit the region, according to a number of seismologists and civil engineers. Should any of the structures fail, reservoirs as large as lakes could empty onto downstream towns and cities. A collapse of Tehri Dam in the central Himalayas, which sits above a fault, would, for instance, release a wall of water about 200 meters high, slamming through two towns. In total, the flooding would affect six urban centers with a combined population of two million.

More powerful earthquakes are indeed likely to strike the Himalayas in coming decades, seismology models show. The Indian subcontinent is pushing under the Tibetan Plateau at roughly 1.8 meters per century, but it regularly gets stuck; when the obstruction gives way, a section of the

Continued on page 16

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PHILIPPINES 2013 © FLORIAN LEMS/MSF

Continued from page 14

India's Tehri Dam blocks Bhagirathi River, a main tributary of the Ganges.

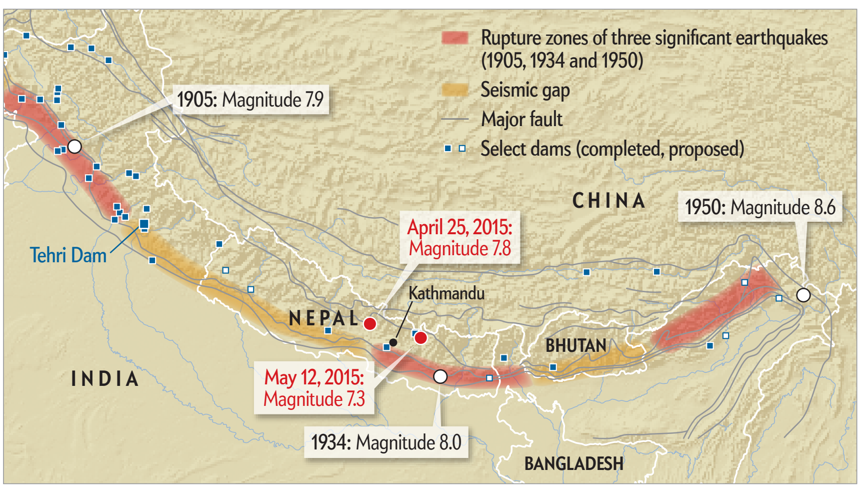
Tibetan plate lurches a few meters southward and releases the pent-up energy in an earthquake. The Nepal earthquakes also destabilized the region to the west, notes Laurent Bollinger, a seismologist at the French Alternative Energies and Atomic Energy Commission. Destabilization makes a great earthquake, which is defined as having a magnitude of 8.0 or higher, more likely to occur sooner rather than later. Other studies indicate that the earthquakes released only a mere fraction of the stress of this fault line, which is expected to readjust with quakes of equal or higher magnitude. "Whether they'll break now, in an 8 or wait another 200 years and then give way in an 8.7, one cannot say," says seismologist Vinod K. Gaur of the CSIR Fourth Paradigm Institute in Bangalore.

Such seismically active regions are exactly where hundreds of dams 15 meters or higher are either under construction or being planned, most of them to supply hydropower to India or China. Any dam being built during this government-funded boom, as well as those already completed, must be able to withstand the strong ground shaking of an extreme earthquake, says Martin Wieland of the International Commission on Large Dams, a group of engineers that makes recommendations for structural standards. Although every nation has its own regulations, India and China are secretive about their dam designs when it comes to public scrutiny. Independent engineers rarely are allowed to evaluate the robustness of the structures, and when they are, the results can be unsettling. For example, Probe International, a Canadian environmental research organization, reports that designers for China's Three Gorges Dam used "the most optimistic interpretation possible" of seismic shaking. Similarly Tehri Dam never underwent realistic simulations, asserts Gaur, who served on its oversight committee, along with civil engineer R. N. Iyengar, formerly of the Indian Institute of Science in Bangalore. Government-affiliated scientists and engineers claim that Tehri Dam can survive an 8.5 shock, but outside experts are not so sanguine. Any of hundreds of dams could be in danger of bursting when the next big one hits. If that were to happen during monsoon season, when the dams are full, the consequences could be catastrophic.

Local corruption can complicate matters, enabling contractors to get away with using substandard materials or deviating from mandated parameters. A 2011 study published in *Nature* found that an overwhelming majority of deaths from building collapse in earthquakes occur in corrupt countries. (*Scientific American* is part of Springer Nature.) What is more, Transparency International, a nongovernmental organization that highlights corruption, identifies public construction works as one of the world's most bribery-prone industries—with dams being of special concern. Scandals involving dam projects have roiled both India and China, to the extent that the former Chinese premier, Zhu Rongji, coined the evocative term "tofu construction" to describe a defective dike.

A handful of scientists who understand the hidden dangers of the Himalayas have taken the lead in arguing for realistic, undisguised assessments aimed at protecting the region's population, though only with limited success. In a case brought by environmentalists against Tehri Dam, the Supreme Court of India sided with government scientists to dismiss safety concerns. And in 2012 seismologist Roger Bilham of the University of Colorado Boulder was deported from the New Delhi airport, in part, he says, for his unwelcome prediction that the Himalayas can sustain a magnitude 9.0 earthquake. Bilham contends that the Indian government has since discouraged foreign collaborations in seismology.

For now, all concerned parties can do is call attention to the problem. "Sunshine is the best disinfectant," says Peter Bosshard of International Rivers in Berkeley, Calif. "Without public scrutiny, it is much easier to get away with cutting corners." Given the stakes, more than sunshine will be necessary: the next great earthquake in the area may well result in a man-made tsunami. *—Madhusree Mukerjee*



Seismologists expect future tremors of magnitude 8.0 or higher in the Himalayas. The risk of great earthquakes is particularly high in seismic gaps, regions on a fault line that have not recently experienced earthquakes. A subset of dams is shown above.

HANS GEORG ROTH *Corbis* (*top*)

Map by Terra Carta

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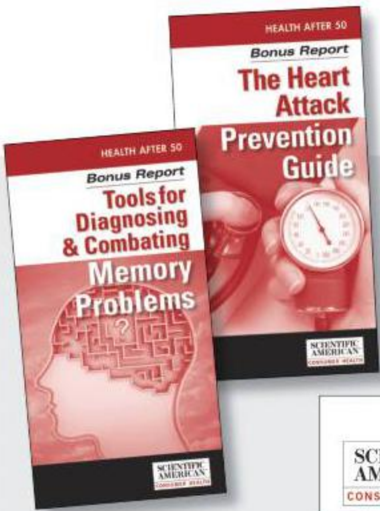

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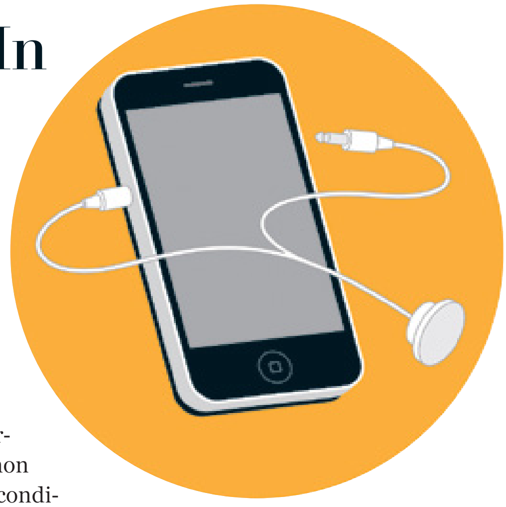
MOBILE TECHNOLOGY

The Doctor Is In (Your Phone)

Smartphone apps in development will help diagnose and manage disease



Celebrities and professional athletes are among the few Americans with doctors and other health care workers at their beck and call. The rest of us typically are left to our own devices perhaps more often than is healthy: common ailments can go undiagnosed, chronic conditions can run amok and serious illnesses can be mistaken for common colds. But “our own devices” has gained new meaning in recent years. Medical researchers are tapping into sensors in the smartphones we carry with us just about everywhere. A forthcoming wave of apps will help diagnose conditions, spot trouble from afar, and provide a window into our day-to-day condition and health stats so we can get care when we need it most. —*Corinne Iozzio*

ResApp

UNIVERSITY OF QUEENSLAND, AUSTRALIA

WHAT IT DOES: Determines the cause of a cough

HOW IT WORKS: Because respiratory diseases, such as pneumonia, alter the structure of the respiratory tract, each one creates a unique sound signature in a patient’s cough. Based on four to five coughs, signal-processing algorithms in this app can detect those patterns, identifying both the type and severity of an ailment.

STATUS: A proof-of-concept trial of 91 patients in 2013 diagnosed pneumonia and asthma with 90 percent accuracy. A second, larger trial is under way; the additional data should allow refinement of the app for bronchitis, bronchiolitis and upper respiratory tract conditions. A version could be ready for release to doctors next year.

PRIORI

UNIVERSITY OF MICHIGAN

WHAT IT DOES: Predicts bipolar episodes before they occur

HOW IT WORKS: This always-on app records a patient’s voice during phone calls, listening for changes in speech patterns, such as speed, that might indicate the onset of a depressive or manic episode. Doctors or caregivers will receive alerts when intervention is needed.

STATUS: A pilot study completed last year correctly identified episodic changes in six patients with type 1 bipolar disorder, which is characterized by severe mood swings. Now researchers are working with a larger group (at least 40 subjects) to further refine the technology, in hopes of producing a beta version of the app by the spring of 2016.

ApneaApp

UNIVERSITY OF WASHINGTON

WHAT IT DOES: Diagnoses sleep apnea, a condition in which breathing repeatedly stops and starts during sleep

HOW IT WORKS: Inaudible sonar sound waves from the phone’s speaker bounce off a patient’s body and back to the phone. Variations in breathing alter the signal, allowing algorithms in the app to determine whether or not apnea is present.

STATUS: An initial laboratory trial has shown ApneaApp to be just as effective as hooking up patients to tracking instruments in a sleep clinic, the most common way to screen for apnea. It correctly classified 32 out of 37 patients (missing only cases that doctors usually would consider borderline). Next, the team will design a trial to test the app in patients’ homes.

Illustrations by Thomas Fuchs

Cracks and ridges crisscross Europa.

COURTESY OF NASA, JPL-CALTECH AND SETI INSTITUTE

PLANETARY SCIENCE

Europa's "Brown Gunk" Suggests a Briny Sea

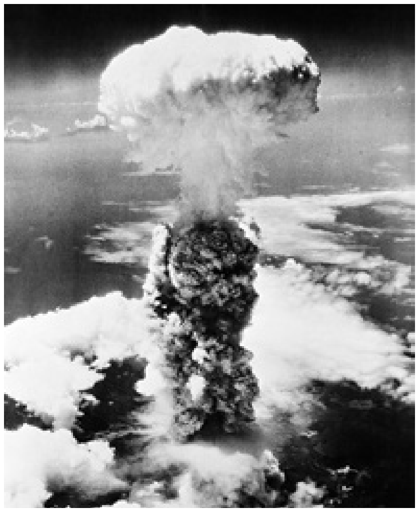
Alien life may flourish in subsurface oceans on Jupiter's Europa, but another of the icy moon's secrets is displayed in plain view: a mysterious "brown gunk" filling many of the fissures, fractures and craters that crisscross its face. "That is our state-of-the-art term for it—brown gunk," says NASA's Curt Niebur, who explained at a recent conference that the unknown substance most likely is carried to the surface by water erupting from Europa's depths. "If we can determine what that brown gunk is," Niebur explains, "we can then understand what is in the water, what is in the oceans of Europa." Those insights could be crucial for learning whether the satellite harbors life.

Two NASA planetary scientists, Kevin Hand and Robert Carlson, have a lead on the case: the gunk may be simple sea salt, just like that in Earth's oceans but baked by radiation. They came to that conclusion after simulating the harsh environment on the moon with a laboratory "Europa-in-a-can," a cryo-cooled vacuum chamber bathed in electron beams. Inside, samples of common table salt turned a yellowish-brown and developed spectroscopic features resembling those observed for Europa's brown gunk. The findings were published in May in *Geophysical Research Letters.*

If irradiated sea salt is indeed the identity of the gunk, that would mean the underlying ocean, like Earth's, is in direct contact with rock and enriched with potentially life-nurturing amounts of minerals. And because the experimental sea salt grew darker the longer it was exposed to the chamber's conditions, in the future scientists might seek out upwellings from the hidden ocean simply by locating the lightest-colored gunk. It won't be long before NASA starts exploring: this spring the space agency announced it will send a mission to Europa in the 2020s. *—Lee Billings*

COMMENT AT ScientificAmerican.com/aug2015

The world witnessed a level of destruction never before seen with the nuclear bombing of Hiroshima on August 6, 1945.



NUCLEAR ENERGY

Remembering the Blast

Survivors of World War II's Hiroshima and Nagasaki bombings speak out on the 70th anniversary of the detonations

Seventy years ago this month U.S. atomic bombs destroyed the cities of Hiroshima and Nagasaki, killing a total of roughly 200,000 Japanese people in the world's first, and so far only, use of nuclear weapons in war. Many of those who survived the initial blast died soon after from injuries, burns and radiation sickness. The scale of the devastation sparked an enduring debate over whether the use of such weapons is ever justifiable and the extent to which scientists are morally responsible for the consequences of their discoveries.

Today some 22,000 atomic bombs exist in at least eight countries, according to the United Nations Office for Disarmament Affairs. More than 65 nations support a worldwide ban on nuclear weapons. Many of the nations that own them, including the U.S., have diminished their stockpiles yet continue to upgrade their nuclear technology.

Several of the *Hibakusha,* or survivors of the blast, and their family members visited *Scientific American*'s New York City office this spring during a trip to attend the 2015 review conference for the 1970 Treaty on the Non-Proliferation of Nuclear Weapons—a meeting that occurs every five years to allow its 190 signatories to evaluate progress. Edited excerpts from the interpreted conversation follow. —*Clara Moskowitz*

WORDS FROM THE SURVIVORS

[After the August 6 bombing of Hiroshima], we decided to leave the town. Many people did the same thing. We took refuge in some vineyards. Because there was no food, we ate the unripe grapes, and then we developed fever and diarrhea and began to vomit. My mother thought we had got dysentery. Now I think it was from radiation poisoning.... Many of the people that I work with have had their children die of leukemia or cancer very young—in their 40s. I worry about myself, but I'm also worried about my children and their health.
—Tamiko Nishimoto, age four when the bomb fell just 2.3 kilometers from her home

On August 8 the bomb was dropped on Nagasaki. I was working for Nagasaki Shipyard. At 11:02 it was like a big sun burning over the building. I was surprised, and I saw something burning outside the window. About five or six seconds later a huge explosion shook the building and sent glass flying everywhere. Those who had been standing near the windows were struck with glass. They had so many holes in them, they looked like pomegranates.... As soon as work ended at five o'clock, I went back to my dormitory in Urakami. Many people were running toward me—not so much running as slowly struggling forward. Their faces were so burned that their faces resembled rugby balls. Their hands were swollen up, and they looked like they were wearing baseball gloves. There was limp skin hanging down from their cheeks and hands. Because it was very hot, people tried to wipe their cheeks with their hands, but they ended up with the skin of both their hands and their cheeks coming down to their chin. When I finally arrived at my dorm at Urakami, it was completely burned, and all the people inside had been killed.
—Takamitsu Nakayama, age 16 during bombing

GETTY IMAGES (*aerial view and mushroom cloud*); AP PHOTO (*ground view*); ELIENE AUGENBRAUN (*survivor portraits*)

TO WATCH THE CONVERSATION ScientificAmerican.com/aug2015/atomic-bomb

ENGINEERING

The Room with the Weakest Magnetic Field on Earth

Five questions the chamber could answer

"Weakest" is rarely a superlative worth celebrating, but experiments began this summer in a room (*below*) with the weakest magnetic field in our solar system—and scientists are excited. Built by physicists at the Technical University of Munich, the room achieves a millionfold reduction in the intensity of ambient magnetic fields, a 10-fold improvement on any previous man-made structure, registering even less such activity than the vast, empty space between planets. The facility's shielding consists of layers of a highly magnetizable metal that ensnare fields so they do not pass through to the structure's interior. Within, ultraprecise experiments can take place with only minute interference from the results-mucking effects of Earth, electronics, living bodies, and more. The room's special type of silence therefore offers a unique opportunity to probe important questions in physics, biology and medicine. —*Sarah Lewin*

COURTESY OF ASTRID ECKERT *Technical University of Munich*

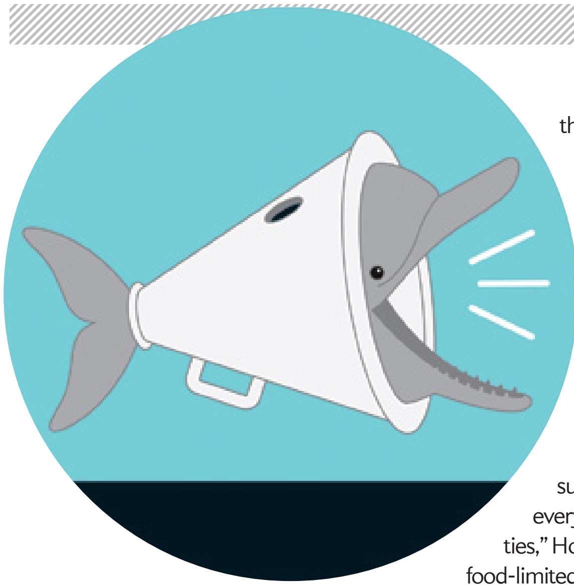
1 Why is there more matter than antimatter in the universe? The Munich physicists will observe whether a neutron's magnetic properties behave evenly in the presence of high electric fields and precisely controlled magnetic fields. Strong discrepancies in how the particles are balanced, such as a slight difference in charge, could hint at how the asymmetry of matter occurred.

2 Do magnetic monopoles exist? If particles with a single pole are out there, they will be able to pass through the room's shielding. Without interference, sensors would register the increased magnetic activity.

3 What is dark matter made of? Researchers plan to monitor the room for theorized "axionlike" dark matter particles, which could affect the spins of some atoms.

4 How do animals use magnetic fields to navigate? By raising organisms in an environment with very little magnetic activity, researchers may be able to discern whether use of such fields is a learned or an innate trait.

5 What can magnetism reveal about human health? Any space with very little magnetic noise opens up the possibility for more detailed diagnoses: for instance, distinguishing the magnetic field of a mother's heart from that of her unborn child to determine irregularities.



ANIMAL BEHAVIOR

Can You Hear Me Now?

Dolphins "shout" to be heard over boat noise—and use up energy to do so

Click! Click-clickity-click-click. Unghhhh. Cliiiiiiiick! A bottlenose dolphin tries to communicate with nearby friends, but they cannot hear the calls. There are too many ships in the water making noise. *CLICK!* To be heard over man-made din, whales and dolphins must effectively raise their voices, which they do by changing the frequency, amplitude or duration of their vocalizations or simply by repeating their calls over and over. Unfortunately, that acoustical alteration also affects the animals' health.

National Oceanic and Atmospheric Administration biologist Marla M. Holt and her colleagues turned to a pair of bottlenose dolphins at the Joseph M. Long Marine Laboratory at the University of California, Santa Cruz, to find out how. The dolphins were trained to produce a quiet, low-amplitude vocalization on command, as well as a high-amplitude call, 10 decibels louder. The researchers monitored the dolphins' oxygen intake during both types of calls and found that the louder the dolphins vocalized, the more oxygen they needed.

The team then combined its observations of oxygen use with data from wild dolphins to calculate how many extra calories the animals would have to eat to compensate for the energy they burn while making louder calls. Wild dolphins, the estimates show, would need to gobble two extra nutritional calories of fish for every two minutes they spend whistling, clicking and squawking to overcome boat noise. Although this metabolic cost is small, it adds up over time. "To survive and breed, you have to make sure you have enough calories every day to support those activities," Holt says, and animals living in food-limited, noisy environments that rely on sound for communication, hunting or breeding may not be able to find enough food to make up the difference. The health risk is even more serious for juveniles and for nursing females, which already must perform additional foraging to obtain all the nutrition they need. The results were published this spring in the *Journal of Experimental Biology.*

Human-created noise underwater, whether from the spin of a ship's blades, the hum of an engine, the clanking of construction or the bangs of seismic exploration, does more than force odontocetes to speak up. Other research shows that whales and dolphins breach, spy-hop and tail slap the surface more often when vessels are nearby, all of which sap more energy. Military sonar also disrupts cetacean hearing and alters their diving behaviors, most likely leading to illness and stranding.

The louder the dolphins vocalized, the more oxygen they needed.

Next, Holt and her colleagues will investigate specific actions that could be taken to mitigate the effects of human-generated noise on dolphins and other sea creatures, such as requiring ships to slow their motors while coming into a harbor or keeping whale-watching boats a minimum distance away from the marine mammals they pursue. Besides, shouldn't humans know better? Interrupting a conversation is rude.

—*Jason G. Goldman*

COMMENT AT ScientificAmerican.com/aug2015

GENETICS

Watch Out, Sam Adams

Scientists make the first new lager yeasts in centuries

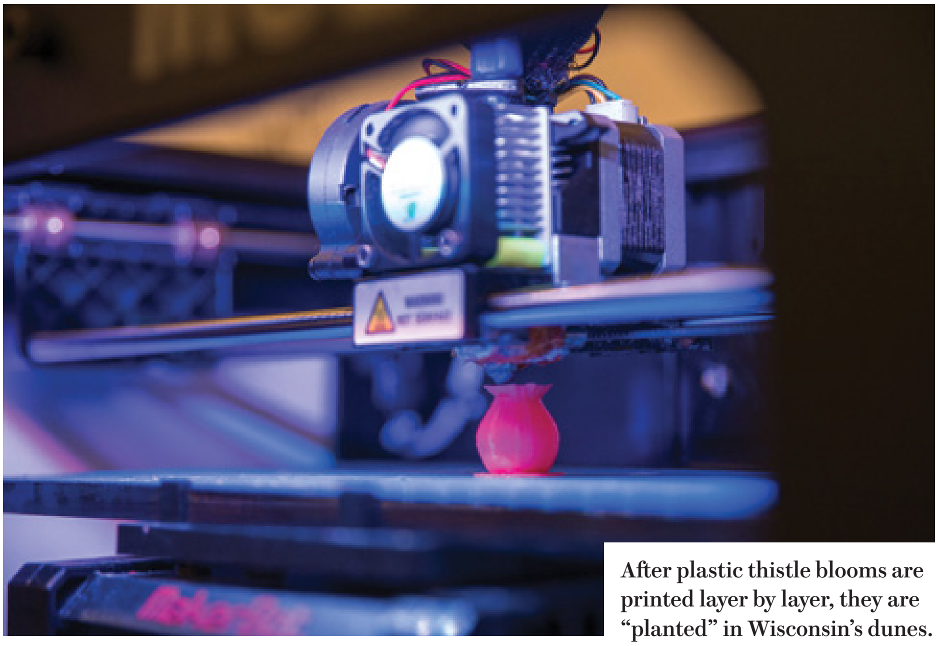
Lagers are boring. When you pop a can of lager beer, you taste the product of closely related strains of *Saccharomyces pastorianus.* Their genetic variety pales in comparison to the small but diverse group of yeasts used for making ale and wine, which pump out vastly different metabolic by-products and a wide range of flavors. In fact, lagers have looked and tasted much the same for hundreds of years because breeding strains with new brewing characteristics and flavors has proved difficult; the hybrids were effectively sterile. But that is about to change.

This good news harks back to the 15th-century origins of lagers. *S. pastorianus* appears to have been bred after an accidental cross of two other yeasts in a cool, dark cave in Bavaria when monks began "lagering," or storing beer. In the 1980s scientists determined the identity of one original parent: *Saccharomyces cerevisiae,* which is the mother of all yeasts used in baking and brewing. The other remained unknown until 2011, when Diego Libkind, an Argentine microbiologist, identified *Saccharomyces eubayanus* in the forests of Patagonia as the missing link. Wild *S. eubayanus* was not well adapted for industrial brewing, but its discovery opened up the possibility of developing new yeast crosses. "Once *eubayanus* was discovered, things suddenly became very interesting," says Brian Gibson, who studies brewing yeasts at the VTT Technical Research Center of Finland in Espoo.

Lager lovers can now officially raise a toast because Gibson and his colleagues recently logged the success of re-creating the ancient fling between *S. cerevisiae* and *S. eubayanus.* "You can now produce lager yeasts that are very different from one another," Gibson says. All the resulting hybrids outperformed their parents, producing alcohol faster and at higher concentrations and turning out tastier products, as documented in a paper published in the *Journal of Industrial Microbiology & Biotechnology.* In particular, they made 4-vinylguaiacol, which resulted in flavors more characteristic of Belgian wheat beers. "The beers have a clovey aroma," Gibson says. "It's actually quite nice but maybe something we don't always want. The idea is to have a whole range of strains, and you just pick and choose." The hunt has now turned to finding new yeast unions that gobble up sugar more effectively, potentially creating lower-calorie beers.

Gibson notes that building up a wide variety of flavorful strains of lagers should be relatively easy, which bodes well for the as yet undisclosed breweries that are adopting the new fermenters. Lager, according to one 2012 estimate, makes up more than three quarters of the U.S. beer market. —*Peter Andrey Smith*

LEE ROGERS *Getty Images*



After plastic thistle blooms are printed layer by layer, they are "planted" in Wisconsin's dunes.

COURTESY OF CHICAGO BOTANIC GARDEN

ECOLOGY

The Great Flower Fabrication

3-D printing may save a threatened thistle

There's something particularly cruel in using beauty to kill, but that's exactly what scientists at the Chicago Botanic Garden set out to do earlier this summer in the sand dunes of northern Wisconsin. There Kayri Havens and her colleagues planted about 60 3-D-printed flowers to lure invasive weevils to their death.

For more than a decade, beginning in the 1990s, scientists deliberately distributed the invasive weevil *Larinus planus* throughout the country to consume Canada thistle, an aggressive weed that had run rampant through American farm fields and rangeland. But like many well-intentioned species-control efforts before it, the plan went awry. The long-snouted insect jumped host and attacked native thistles, including the Pitcher's thistle, a flowering spiky plant that grows only in the Great Lakes region and was listed as a threatened species in 1988 by the U.S. Fish and Wildlife Service in response to habitat destruction. Left to its own devices, the seed-eating weevil could cut the Pitcher thistle's possible time to extinction in half, Havens says.

She now hopes the 3-D-printed thistle fakes will come to control the biocontrols. The plastic purple, blue or white flowers—some halfway open, others in full bloom—sit atop 20-inch-long dowels alongside the real things on Wisconsin's Door County peninsula. Most are outfitted with cotton wicks saturated in a lemony or wintergreen scent, both known to attract weevils. "We needed a chemical signature that weevils go crazy over," says botanist Pati Vitt. Video cameras currently capture faunal activity at the faux-studded floral plots so researchers can catalogue which models the weevils favor, the number of insects that visit and how long they stay. Once the scientists discern the shape, color and smell combo that attracts the weevils—but not bees and other pollinators—a trap will be designed. It could take a few years to determine all the particulars, so for now the weevils that take a shine to the 3-D-printed blooms are captured by hand when possible and thrown in soapy water to die. If the counterfeit scheme works, fields of 3-D-printed flowers might one day stand guard over Wisconsin's dunes. *—Debra Weiner*

MORE 3-D-PRINTED FAKES

DECOY INSECTS

Pennsylvania State University entomologists have set out to kill emerald ash borers, a tiny beetle that destroys ash trees, with electrified 3-D-printed duplicates. When (real) male ash borers land on (fake) females in hopes of mating, the six-legged lotharios receive a fatal shock.

WILDFLOWERS

Plastic flowers printed in an array of shapes are helping researchers at the University of Washington tease out how pollinators, such as the hummingbirdlike hawk moth, pick certain blossoms for feeding.

MOCK EGGS

Cowbirds, which get other birds to raise their young, often lay their eggs in robin nests. The robins have a decent "not mine" meter, however, and frequently cast out the foreign ova. To determine which characteristics tip the moms off, Hunter College ornithologists snuck a variety of 3-D-printed eggs into robin nests. They discovered that intruders are identified by color.

—Kat Long and Sarah Lewin

COMMENT AT ScientificAmerican.com/aug2015

IN THE NEWS

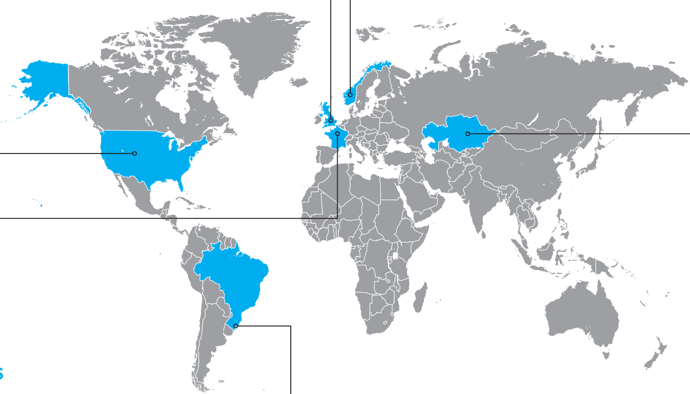
Quick Hits

U.K.

An aerospace laboratory in Stevenage is in the midst of a three-month microbe-killing "bake-off" in preparation for the construction of the European Space Agency's ExoMars rover. The rover is scheduled to land on the Red Planet in 2019—without earthly contaminants, it is hoped.

NORWAY

Electric cars 50,000 strong now navigate Norway's roads, a government-set goal met two years ahead of schedule. The zero-emissions vehicles make up nearly 25 percent of all cars sold in the country thanks to incentives such as free parking and zero sales tax.



U.S.

A team of American and German physicists measured the radiation emitted from a single, orbiting electron for the first time.

KAZAKHSTAN

As of June, an unknown illness has killed more than 120,000 saigas, critically endangered antelopes that live throughout Central Asia—about half their global population.

FRANCE

Parisian lawmakers are cracking down on noise pollution. One new mandate: an acoustic asphalt coating on the city's peripheral highway, which could reduce noise by 7.5 decibels (equivalent to a one-sixth reduction in traffic).

BRAZIL

A letter written by Albert Einstein in 1951 was found in a safe at a Jesuit school in Porto Alegre. Addressing students, the Nobel laureate wrote, "Thinking is to man what flying is to birds. Don't follow the example of a chicken when you could be a lark."

ANTARCTICA

Climate scientists analyzed the chemical composition of million-year-old air—the most ancient air ever recovered from pockets deep within a glacier.

For more details, visit www.ScientificAmerican.com/aug2015/advances

MICROBIOLOGY

What Meets the Eye

Contact lenses dictate what lives on the eye's surface

People who wear contact lenses often acquire unwelcome microbial guests along with the convenience afforded by this eyewear. In fact, a higher diversity of bacteria lives on the eye surface of lens wearers than that of the naked-eye crowd, according to an extensive classification effort by microbiologists at New York University's Langone Medical Center. This difference may help explain why lens poppers develop eye infections up to seven times more frequently than they would otherwise.

In an effort to map the ocular microbiome, the researchers sequenced hundreds of swabs from the eyes and eyelids of 11 people who do not wear lenses and nine of those who do. Wearers had about three times the typical proportion of *Methylobacterium, Lactobacillus, Acinetobacter* and *Pseudomonas* bacteria. Although the first three bugs are typically harmless, *Pseudomonas* entering a scratched cornea can result in an infection, triggering redness, pain and blurred vision. Left untreated, the condition may lead to blindness. These same bacterial groups tend to hang out innocuously on our skin, says N.Y.U.'s Lisa Park. This means they most likely hitch a ride on users' fingers during the act of inserting lenses, suggesting an instantaneous shift in the regional microbiome.

Additional results from the study support such a conclusion: the researchers found that the composition of bacteria living on the eyes of people who sport disposable lenses was more similar to that of their skin than was the case among people who don't need lenses. "It's not a definitive connection," Park says, "but it's very intriguing." The physical characteristics of the lenses themselves, such as the pressure they place on the eye, could also foster bacterial growth.

All told, the researchers identified about 10,000 distinct strains of bacteria in their samples. Knowing the exact microbial community in a patient's eye could help doctors treat infections with targeted antibiotics, says Jack Gilbert, a microbiologist at the University of Chicago who was not affiliated with the study.

To avoid infections altogether, however, contact lens wearers should assiduously follow best practices with their eyesight enhancers: wash hands thoroughly before handling lenses, use fresh saline solution to rinse and store them, and replace cases every three months. At least that way, the welcome mat for tiny, menacing orbital guests should shrink. —*Kat Long*

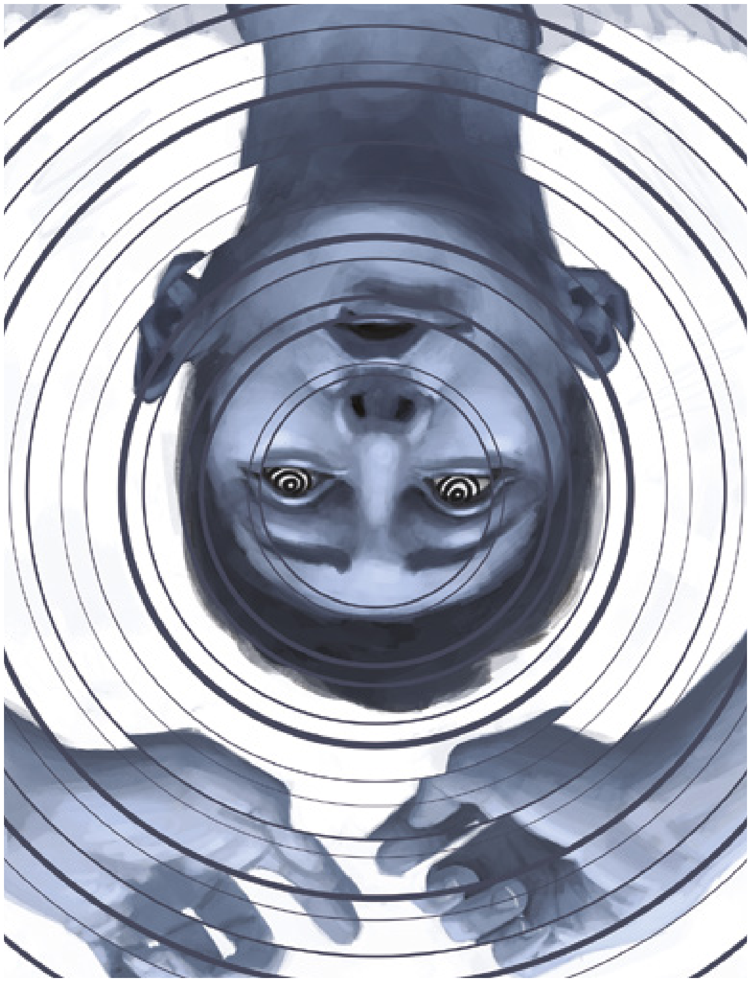
GETTY IMAGES

COMMENT AT ScientificAmerican.com/aug2015

David Noonan, who wrote about surgery for snoring in the June issue, is a freelance writer who specializes in science and medicine.

A Turn for the Worse

Vertigo can knock people off their feet for years. Ear implants and gene therapy are new attempts at relief



Leaping through the air with ease and spinning in place like tops, ballet dancers are visions of the human body in action at its most spectacular and controlled. Their brains, too, appear to be special, able to evade the dizziness that normally would result from rapid pirouettes. When compared with ordinary people's brains, researchers found in a study published early this year, parts of dancers' brains involved in the perception of spinning seem less sensitive, which may help them resist vertigo.

For millions of other people, it is their whole world, not themselves, that suddenly starts to whirl. Even the simplest task, like walking across the room, may become impossible when vertigo strikes, and the condition can last for months or years. Thirty-five percent of adults older than 39 in the U.S.—69 million people—experience vertigo at one time or another, often because of damage to parts of the inner ear that sense the body's position or to the nerve that transmits that information to the brain. Whereas drugs and physical therapy can help many, tens of thousands of people do not benefit from existing treatments. "Our patients with severe loss of balance have been told over and over again that there's nothing we can do for you," says Charles Della Santina, an otolaryngologist who studies inner ear disorders and directs the Johns Hopkins Vestibular NeuroEngineering Laboratory.

Steve Bach's nightmare started in November 2013. The construction manager was at home in Parsippany, N.J. "All of a sudden the room was whipping around like a 78 record," says Bach, now age 57. He was curled up on the living room floor in a fetal position when his daughter found him and called 911. He spent the next five days in the hospital. "Sitting up in bed," he recalls, "was like sitting on top of a six-foot ladder." Bach's doctors told him that his left inner ear had been inflamed by a viral infection. He underwent six months of physical therapy to train his brain and his healthy right ear to compensate for the lost function in his left. It helped, and he returned to his job in May 2014. Even so, this spring he was still having unsteady moments as he made his way around a construction site. "Whatever is in your brain that tells you when your foot is going to hit the ground to keep you upright, I don't have 100 percent of that," he says. Vertigo can also trigger severe anxiety and depression, impair short-term memory, disrupt family life and derail careers.

Such crippling difficulties are prompting physicians to test new treatments for the most severe vertigo cases, Della Santina says. He is starting a clinical trial of prosthetic implants for the inner ear. Other doctors are experimenting with gene therapy to fix inner ear damage. And the work with dancers is beginning to reveal novel aspects of brain anatomy involved with balance, parts that could be targets for future treatments.

The ears are key to keeping us upright and stable because they hold an anatomical marvel known as the peripheral vestibular system. This is a tiny arrangement, in each ear, of fluid-filled loops, bulbs and microscopic hair cells. The hairs are topped by a mem-

Illustration by Bernard Lee

brane embedded with even tinier calcium carbonate crystals. When the head moves, the crystals pull on the hairs and combine with the other bits of anatomy to relay information about motion, direction and speed to the vestibular nerve. The nerve passes it on to a region at the stem of the brain called the cerebellum, as well as other neural areas. The brain then activates various muscles and the visual system to maintain balance.

The list of things that can go wrong with this delicate system is long. Causes of inner ear vertigo include tumors, bacterial and viral infections, damage from certain antibiotics, and Meniere's disease, a chronic condition characterized by recurring bouts of vertigo, hearing loss and tinnitus that experts estimate to affect an additional five million people. The most common vestibular disorder is benign paroxysmal positional vertigo, or BPPV. It occurs when renegade crystals get loose, float into the vestibular loops and generate a false sensation of movement. Fortunately, this type of problem is usually treated effectively with physical therapy involving a repeated set of slow head movements that float the crystals out of the loops.

But physical therapy does not help everyone or, as in Bach's case, does not heal the person completely. Some patients have lost vestibular function in both ears. For them, Della Santina and his colleagues at Johns Hopkins have been developing an implant that substitutes mechanical components for damaged inner ear anatomy. Once the researchers get the green light from the U.S. Food and Drug Administration, they will begin testing their invention, called a multichannel vestibular implant, in humans. The device is modeled on the cochlear implants that have restored hearing for thousands of people since the first one was used in 1982. These implants use a microphone to pick up sound vibrations and transmit them to the brain via the auditory nerve. Instead of a microphone, a vestibular implant has two miniature motion sensors that track the movement of the head. One, a gyroscope, measures the motion of the head as a person looks up, down and around a room. The other, a linear accelerometer, measures directional movement, such as walking straight ahead or down a flight of stairs. And instead of breaking sound into different frequency components and sending them to the auditory nerve, the motion sensors send the signals connoting head position and movement to the vestibular nerve.

Results from the trial of a different vestibular implant in four patients with Meniere's disease at the University of Washington were mixed. Although it worked well initially, the effect petered out after a few months. But the Johns Hopkins device has a different design and will be used in patients with disorders other than Meniere's, so the physicians hope the outcomes will be better.

Sixty-nine million U.S. adults older than 39 experience vertigo, and tens of thousands do not benefit from existing treatments.

EAR GENES

ANOTHER STRATEGY being tested in humans involves a gene that controls hair cell growth in the inner ear. During embryonic development, the *ATOH1* gene directs the creation of these cells, which are crucial for hearing and balance. The gene stops working at birth, leaving humans with a fixed number of hairs—and problems if the hairs are damaged. In an early FDA-approved clinical trial targeting balance and hearing, researchers led by Hinrich Staecker, an otolaryngologist at the University of Kansas, are injecting the gene into the ears of 45 patients with severe hearing loss, under general anesthesia. In experiments on mice with severe inner ear damage, the compound restored hair cell levels to 50 percent of normal, with some improvement in hearing. If the experimental compound, called CGF166, has similar effects in people, it could launch a new era in the treatment of vestibular disorders.

Gene therapy needs to be handled carefully; it can trigger serious immune system reactions, and patients in other experiments have died. Safety factors in this trial include a gene that can be turned on only in the targeted cells, Staecker says, and a minuscule dose that does not circulate through the body. In addition, he explains, the viral jacket around the gene, which helps it penetrate cells, has been deployed "without safety problems" in about 1,500 people in previous experiments with different genes.

Even if such research succeeds, major gaps in our basic knowledge about disabling dizziness remain. For example, doctors do not know why the ear crystals get loose in the first place. These gaps are why some researchers turned to ballet dancers. The idea is to study especially robust vestibular systems to better understand the mysteries of unhealthy ones.

A team at Imperial College London used a battery of tests and brain imaging to investigate the ability of expert ballet dancers to resist vertigo while performing multiple pirouettes. The scientists studied 29 female dancers with an average of 16 years of training—the dancers started at or before age six—and compared them with female rowers. The more experienced and highly trained dancers had a lower density of neurons in parts of the cerebellum where dizziness is perceived, the group reported this year in the journal *Cerebral Cortex.* The anatomy is smaller, the researchers think, because the dancers continually suppress the perception of dizziness. During pirouettes, dancers focus their eyes on a fixed point for as long as possible. The technique, called spotting, limits the sensory signals sent to the brain. This "active effort to resist dizziness" during years of training also left the dancers in the study with a smaller, slower network of neuron connections in a part of the right hemisphere of the brain where those signals are processed.

This kind of suppression might someday offer relief to patients with chronic vertigo, if ways can be found to develop it in nondancers using physical therapy, the scientists suggest. For thousands of patients, it would be a turn for the better. SA

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

The Touch Screen Generation

Are mobile devices ruining today's children? Science weighs in

You've met the cluck-cluckers—the people who automatically decry every new technology. "All this newfangled gadgetry is rotting our brains," they say, "and ruining our kids."

Every older generation disapproves of the next; that's predictable and human. Apparently digital devices are ruining our youth, just the way that rock music ruined their parents, and television ruined their parents and motorcars ruined theirs. So I guess we've been ruined for generations.

But I got to wondering: What does science say about the ruinous effects of the latest technology?

Part of the answer depends on your definition of "ruining." True, things are different now. Most American kids no longer "go outside and play," unattended, for hours (the stickball industry may never recover). Students no longer need memorize the presidents and the periodic table, because Google is just a keystroke away. We are also losing old skills. Few kids know how to use carbon paper or tend horses; handwriting and driving skills may be next.

Still, different is not the same as worse. And, as I discovered, it's surprisingly difficult to find studies linking modern gadgets (touch screen tablets and smartphones) to the ruination of youth. Research takes time, and the touch screen era is very young. Nobody had ever even seen an iPad, for example, until 2010.

There is, however, early research out—and it provides some insight into how these suddenly ubiquitous gadgets might be affecting kids. One study, published in the February issue of *Pediatrics,* found that children who sleep near a small screen get an average of 21 fewer minutes of sleep than kids without gadgets in their rooms. (As for the reason: the researchers suppose that kids are staying up late to use their gadgets, or maybe light from the screen produces "delays in circadian rhythm.")

What about social skills? Last fall a study at the University of California, Los Angeles, examined 51 sixth graders who spent five days at a nature camp without electronics and 54 who did not. Afterward, the first group did better at reading human emotions in photographs.

Then there was a 2009 Stanford University study, which linked the modern teenager's multitasking computer habits (which would seem to carry over to phones and tablets) with the loss of the ability to focus. That one's a little scary.

What about brain cancer from cell phones? Surely it's bad for these kids to have a radio antenna plastered to their head all day! Well, first of all, if you know any kids, you don't need a study to tell you that they very rarely do put their phone to their head; they would far rather text than make phone calls. And anyway, studies haven't found any link between cell-phone use and cancer.

Time to start cluck-clucking? Not necessarily; not all the studies draw distressing conclusions. In 2012 the nonprofit tech review group Common Sense Media found that more than half of American teens feel that social media—now accessibly anywhere thanks to touch screens—has helped their friendships (only 4 percent report that it has hurt). In 2014 the U.K.'s National Literacy Trust found that poor children with touch screen devices at home are twice as likely to read every day. Also, a study published in *Computers in Human Behavior* found that texting is beneficial for the emotional well-being of teenagers—especially introverts.

Clearly, we still need broader, longer-term studies before we begin a new round of cluck-clucking. And they are coming; for example, results of a huge British survey of 2,500 children called SCAMP (Study of Cognition, Adolescents and Mobile Phones) will arrive in 2017.

In the meantime, the warning bells raised by early research are not loud enough to make us rip our kids' touch screens away and move to Amish country. Yet they are already enough to suggest practicing a very wise, ancient precaution: moderation. Too much of anything is bad for children—whether it is modern electronics, watching TV or playing stickball. SA

SCIENTIFIC AMERICAN ONLINE
Latest research on kids and touch screens: ScientificAmerican.com/aug2015/pogue

Illustration by Harry Campbell

The First Humans

About 2 million years ago the first humans appeared in Africa. Discover what drove their evolution and led to a spread from their homeland to Asia and Europe. Could a controversial find on the far-away island of Flores, in Indonesia, be a relic of these early stages of human evolution? Find out.

The Neanderthals: Another Kind of Human

Our close relatives the Neanderthals evolved in parallel with our own species. They are often depicted as bestial ape-men, but in reality they walked upright as well as we do, and their brains were as large as ours. Track the evolution of the Neanderthals in light of the latest discoveries — and be open to surprises.

The Rise of Homo Sapiens

Modern humans are characterized by large brains and creativity. How did our species arise and spread across the world and how did we interact with other human species? Delve into the origins of human behavioral traits such as complex technology, symbolism and burial of the dead for insights into essential humanness.

Astrophysics

Speaker: Glenn Starkman, Ph.D.

The State of the Universe Report

The universe is big and getting bigger at an accelerating rate. Hear the latest thoughts on cosmic microwave background radiation, supernovae and other phenomena that give us information on the early universe, cosmic expansion, and the large-scale structure of the universe.

In the Beginning

First there was something, then there was much, much more. What was that something, and how did it become everything we see in the universe? Explore these deep questions and lay the groundwork for our subsequent sessions delving into dark matter and inflation.

Oh Dear, What Could Dark Matter Be?

Physicists thought they were going to make dark matter at CERN's Large Hadron Collider, but it's nowhere to be seen. Others have been hoping to make it by shining lasers on concrete, but nothing gets through. So what is dark matter anyway? Get up to speed on current theories and the quest to detect dark matter.

Dissonance in the Cosmic Symphony

The Standard Model of Cosmology is awfully good at explaining a lot about the universe — but not everything. For example, we don't know what's causing the dark energy that's pulling space apart. Hear about prospects for addressing these mysteries and how they are presenting new areas of research for the undaunted physicist.

Mathematics

Speaker: Michael Starbird, Ph.D.

The Five Elements of Effective Thinking

A romantic belief is that brilliant thinkers magically produce brilliant ideas. In truth, however, brilliant innovators practice habits of thinking that inevitably carry them step by step to works of genius. Learn to hone your skills in effective thinking to create new insights, ideas and solutions.

To Infinity … and Beyond

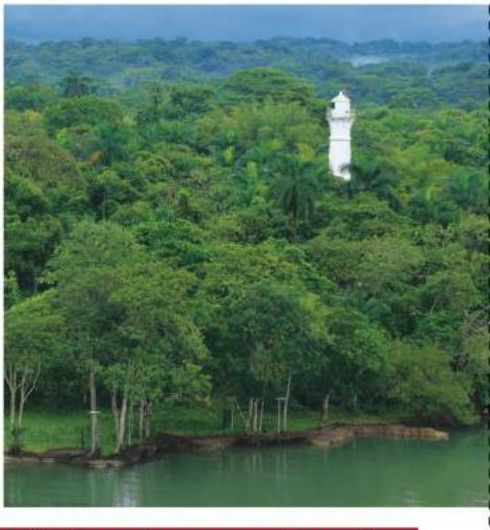
People once thought infinity was incomprehensible — an idea so vast that understanding it was beyond the scope of our finite minds. But we'll create a framework to study infinity and use models from a child's method of sharing to take us to a new understanding of infinity and beyond.

The Fourth Dimension

Untying knots, stealing gold bricks from closed iron safes, and unfolding hypercubes are all part of a journey in the fourth dimension. By applying the basic principles of mathematical thinking to the fourth dimension, we'll explore how deep understanding of the simple and familiar is the key to investigating the complex and mysterious.

Expect the Unexpected

Whether we flip a coin, look at data or ask for birthdays, we find that our intuition about what to expect from random chance is often far from what actually happens. Deepen your understanding of the nature and workings of probability and randomness so you can leverage them as reasoning tools.



EVOLUTION

THE MOST INVASIVE SPECIES OF ALL

Many human species have inhabited the earth. But ours is the only one that colonized the entire planet. A new hypothesis explains why

By Curtis W. Marean

Curtis W. Marean is a professor at the School of Human Evolution and Social Change at Arizona State University and associate director of the university's Institute of Human Origins. Marean is also an honorary professor at Nelson Mandela Metropolitan University in South Africa. He is particularly interested in the origins of modern humans and the occupation of coastal ecosystems. His research is funded by the National Science Foundation and the Hyde Family Foundations.

SOMETIME AFTER 70,000 YEARS AGO OUR SPECIES, *HOMO SAPIENS,* LEFT AFRICA TO BEGIN its inexorable spread across the globe. Other human species had established themselves in Europe and Asia, but only our *H. sapiens* ancestors ultimately managed to push out into all the major continents and many island chains. Theirs was no ordinary dispersal. Everywhere *H. sapiens* went, massive ecological changes followed. The archaic humans they encountered went extinct, as did vast numbers of animal species. It was, without a doubt, the most consequential migration event in the history of our planet.

Paleoanthropologists have long debated how and why modern humans alone accomplished this astonishing feat of dissemination and dominion. Some experts argue that the evolution of a larger, more sophisticated brain allowed our ancestors to push into new lands and cope with the unfamiliar challenges they faced there. Others contend that novel technology drove the expansion of our species out of Africa by allowing early modern humans to hunt prey—and dispatch enemies—with unprecedented efficiency. A third scenario holds that climate change weakened the populations of Neandertals and other archaic human species that were occupying the territories outside Africa, allowing modern humans to get the upper hand and take over their turf. Yet none of these hypotheses provides a comprehensive theory that can explain the full extent of *H. sapiens*' reach. Indeed, these theories have mostly been proffered as explanations for records of *H. sapiens* activity in particular regions, such as western Europe. This piecemeal approach to studying *H. sapiens*' colonization of the earth has misled scientists. The great human diaspora was one event with several phases and therefore needs to be investigated as a single research question.

Excavations I have led at Pinnacle Point on the southern coast of South Africa over the past 16 years, combined with theoretical advances in the biological and social sciences, have recently led me to an alternative scenario for how *H. sapiens* conquered the globe. I think the diaspora occurred when a new social behavior evolved in our species: a genetically encoded penchant for cooperation with unrelated individuals. The joining of this unique proclivity to our ancestors' advanced cognitive abilities enabled them to nimbly adapt to new environments. It also fostered innovation, giving rise to a game-changing technology: advanced projectile weapons. Thus equipped, our ancestors set forth out of Africa, ready to bend the whole world to their will.

A DESIRE TO EXPAND

TO APPRECIATE JUST HOW extraordinary *H. sapiens*' colonization of the planet was, we must page back some 200,000 years to the dawning of our species in Africa. For tens of thousands of years, these anatomically modern humans—people who looked like us—stayed within the confines of the mother continent. Around 100,000 years ago one group of them made a brief foray into

IN BRIEF

Of all the human species that have lived on the earth, only *Homo sapiens* managed to colonize the entire globe.

Scientists have long puzzled over how our species alone managed to disperse so far and wide.

A new hypothesis holds that two innovations unique to *H. sapiens* primed it for world domination: a genetically determined propensity for cooperation with unrelated individuals and advanced projectile weapons.

the Middle East but was apparently unable to press onward. These humans needed an edge they did not yet have. Then, after 70,000 years ago, a small founder population broke out of Africa and began a more successful campaign into new lands. As these people expanded into Eurasia, they encountered other closely related human species: the Neandertals in western Europe and members of the recently discovered Denisovan lineage in Asia. Shortly after the moderns invaded, the archaics went extinct, although some of their DNA persists in people today as a result of occasional interbreeding between the groups.

Once modern humans made it to the shores of Southeast Asia, they faced a seemingly limitless and landless sea. Yet they pushed on, undaunted. Like us, these people could envision and desire new lands to explore and conquer, so they built oceanworthy vessels and set out across the sea, reaching Australia's shores by at least 45,000 years ago. The first human species to enter this part of the world, *H. sapiens* quickly filled the continent, sprinting across it with spear-throwers and fire. Many of the largest of the strange marsupials that had long ruled the land down under went extinct. By about 40,000 years ago the trailblazers found and crossed a land bridge to Tasmania, although the unforgiving waters of the southernmost oceans denied them passage to Antarctica.

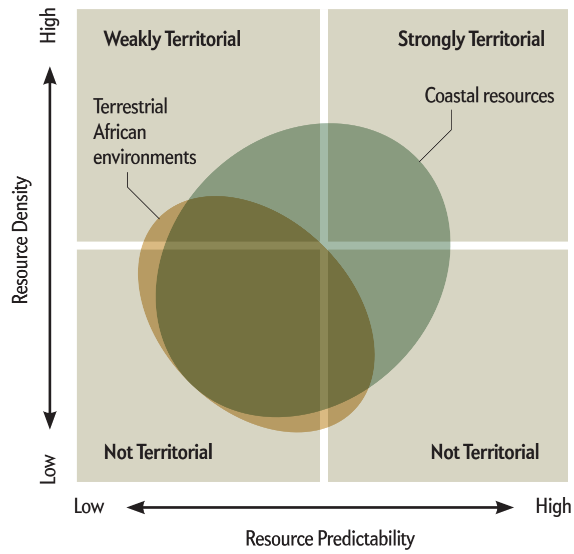
On the other side of the equator, a population of *H. sapiens* traveling northeast penetrated Siberia and radiated across the lands encircling the North Pole. Land ice and sea ice stymied their entry into the Americas for a time. Exactly when they finally crossed into the New World is a matter of fierce scientific debate, but researchers agree that by around 14,000 years ago they broke these barriers and swept into a continent whose wildlife had never seen human hunters before. Within just a few thousand years they reached southernmost South America, leaving a mass extinction of the New World's great Ice Age beasts, such as mastodons and giant sloths, in their wake.

Madagascar and many Pacific islands remained free of humans for another 10,000 years, but in a final push, mariners discovered and colonized nearly all these locales. Like the other places in which *H. sapiens* established itself, these islands suffered the hard hand of human occupation, with ecosystems burned, species exterminated and environments reshaped to our predecessors' purposes. Human colonization of Antarctica, for its part, was left for the industrial age.

THEORY

Worth Fighting For

A classic theory of biology holds that natural selection will favor aggressive defense of food sources (territoriality) when the benefits of exclusive access to these sources outweigh the costs of patrolling them. Among humans living in small societies, territoriality pays off when resources are dense and predictable. In Africa, certain coastal areas have dense and predictable food sources in the form of shellfish beds. Such environments probably triggered territoriality in early *H. sapiens* groups.



SOURCE: CURTIS W. MAREAN, AFTER "HUMAN TERRITORIALITY: AN ECOLOGICAL REASSESSMENT," BY RADA DYSON-HUDSON AND ERIC ALDEN SMITH, IN *AMERICAN ANTHROPOLOGIST*, VOL. 80, NO. 1; MARCH 1978

TEAM PLAYERS

SO HOW DID *H. SAPIENS* DO IT? How, after tens of thousands of years of confinement to the continent of their origin, did our ancestors finally break out and take over not just the regions that previous human species had colonized but the entire world? A useful theory for this diaspora must do two things: First, it must explain why the process commenced when it did and not before. Second, it must provide a mechanism for rapid dispersal across land and sea, which would have required the ability to adapt readily to new environments and to displace any archaic humans found in them. I propose that the emergence of traits that made us, on one hand, peerless collaborators and, on the other, ruthless competitors best explains *H. sapiens*' sudden rise to world domination. Modern humans had this unstoppable attribute; the Neandertals and our other extinct cousins did not. I think it was the last major addition to the suite of characteristics that constitute what anthropologist Kim Hill of Arizona State University has called "human uniqueness."

We modern humans cooperate to an extraordinary degree. We engage in highly complex coordinated group activities with people who are not kin to us and who may even be complete strangers. Imagine, in a scenario suggested by anthropologist Sarah Blaffer Hrdy of the University of California, Davis, in her 2009 book *Mothers and Others,* a couple of hundred chimps lining up, getting on a plane, sitting for hours extremely passively and then exiting like robots on cue. It would be unthinkable—they would battle one another nonstop. But our cooperative nature cuts both ways. The same species that leaps to the defense of a persecuted stranger will also team up with unrelated individuals to wage war on another group and show no mercy to the competition. Many of my colleagues and I think that this proclivity for collaboration—what I call hyperprosociality—is not a learned tendency but instead a genetically encoded trait found only in *H. sapiens*. Some other animals may show glimmers of it, but what modern humans possess is different in kind.

The question of how we came to have this genetic predisposition toward our extreme brand of cooperation is a tricky one. But mathematical modeling of social evolution has yielded some valuable clues. Sam Bowles, an economist at the Santa Fe Institute, has shown that an optimal condition under which

Graphic by Jen Christiansen

genetically encoded hyperprosociality can propagate is, paradoxically, when groups are in conflict. Groups that have higher numbers of prosocial people will work together more effectively and thus outcompete others and pass their genes for this behavior to the next generation, resulting in the spread of hyperprosociality. Work by biologist Pete Richerson of U.C. Davis and anthropologist Rob Boyd of Arizona State additionally indicates that such behavior spreads best when it begins in a subpopulation and competition between groups is intense and when overall population sizes are small, like the original population of *H. sapiens* in Africa from which all modern-day people are descended.

Hunter-gatherers tend to live in bands of about 25 individuals, marry outside the group and cluster into "tribes" tied together by mate exchange, gifting, and common language and traditions. They also sometimes fight other tribes. They take great risks in doing so, however, which raises the question of what triggers this willingness to engage in risky combat.

Insights into when it pays to fight have come from the classic "economic defendability" theory advanced in 1964 by Jerram Brown, now at the University at Albany, to explain variation in aggressiveness among birds. Brown argued that individuals act aggressively to attain certain goals that will maximize their survival and reproduction. Natural selection will favor fighting when it facilitates these goals. One major goal of all organisms is to secure a food supply, so if food can be defended, then it follows that aggressive behavior in its defense should be selected for. If the food cannot be defended or is too costly to patrol, then aggressive behavior is counterproductive.

With the joining of projectile weapons to hyperprosocial behavior, a spectacular new creature was born.

In a classic paper published in 1978, Rada Dyson-Hudson and Eric Alden Smith, both then at Cornell University, applied economic defendability to humans living in small societies. Their work showed that resource defense makes sense when resources are dense and predictable. I would add that the resources in question must be crucial to the organism—no organism will defend a resource it does not need. This principle still holds today: ethnic groups and nation-states fight viciously over dense, predictable and valued resources such as oil, water and productive agricultural land. An implication of this territoriality theory is that the environments that would have fostered intergroup conflict, and thus the cooperative behaviors that would have enabled such fighting, were not universal in early *H sapiens*' world. They were restricted to those locales where high-quality resources were dense and predictable. In Africa, terrestrial resources are, for the most part, sparse and unpredictable, which explains why most of the hunter-gatherers there who have been studied invest little time and energy in defending boundaries. But there are exceptions to this rule. Certain coastal areas have very rich, dense and predictable foods in the form of shellfish beds. And the ethnographic and archaeological records of hunter-gatherer warfare worldwide show that the highest levels of conflict have occurred among groups who used coastal resources, such as those in coastal Pacific North America.

When did humans first adopt dense and predictable resources as a cornerstone of their diet? For millions of years our ancient ancestors foraged for terrestrial plants and animals, as well as some inland aquatic foods on occasion. All these comestibles occur at low densities, and most are unpredictable. For this reason, our predecessors lived in highly dispersed groups that were constantly traveling in search of their next meal. But as human cognition grew increasingly complex, one population figured out how to make a living on the coast by eating shellfish. My team's excavations at the Pinnacle Point sites indicate that this shift began by 160,000 years ago on the southern shores of Africa. There, for the first time in the history of humankind, people started targeting a dense, predictable and highly valued resource—a development that would lead to major social change.

Genetic and archaeological evidence suggests that *H. sapiens* underwent a population decline shortly after it originated, thanks to a global cooling phase that lasted from around 195,000 to 125,000 years ago. Seaside environments provided a dietary refuge for *H. sapiens* during the harsh glacial cycles that made edible plants and animals hard to find in inland ecosystems and were thus crucial to the survival of our species. These marine coastal resources also provided a reason for war. Recent experiments on the southern coast of Africa, led by Jan De Vynck of Nelson Mandela Metropolitan University in South Africa, show that shellfish beds can be extremely productive, yielding up to 4,500 calories per hour of foraging. My hypothesis, in essence, is that coastal foods were a dense, predictable and valuable food resource. As such, they triggered high levels of territoriality among humans, and that territoriality led to intergroup conflict. This regular fighting between groups provided conditions that selected for prosocial behaviors within groups—working together to defend the shellfish beds and thereby maintain exclusive access to this precious resource—which subsequently spread throughout the population.

WEAPON OF WAR

WITH THE ABILITY to operate in groups of unrelated individuals, *H. sapiens* was well on its way to becoming an unstoppable force. But, I surmise, it needed a new technology—projectile weaponry—to reach its full potential for conquest. This invention was a long time in the making. Technologies are additive: they build on prior experiments and knowledge and become increasingly complex. The development of projectile weapons would have followed the same trajectory, most likely evolving from stabbing stick, to hand-cast spear, to leverage-assisted casting spear (atlatl), to bow and arrow, and finally to all the wildly inventive ways contemporary humans have come up with to launch deadly objects.

With each new iteration, the technology became more lethal. Simple wood spears with shaved points tend to produce a puncture wound, but such an injury has limited impact because it does not bleed the animal quickly. Tipping the spear with a sharpened stone increases the trauma of the wound. This elaboration requires several connected technologies, however: one must be able to shape a tool into a point that will penetrate an animal and shape a base that can be attached to a spear. It also requires some type of connecting technology to secure the stone point to the wood shaft—either glue or a tying material, sometimes both. Jayne Wilkins, now at the University of Cape Town in South Africa, and her colleagues have shown that stone tools from a site in South Africa called Kathu Pan 1 were used as spearpoints some 500,000 years ago.

The antiquity of the Kathu Pan 1 find implies that it is the handiwork of the last common ancestor of Neandertals and modern humans, and later remains from 200,000 years ago show that, as one might expect, both descendant species made these kinds of tools, too. This shared technology means that, for a time, there was a balance of power between Neandertals and early *H. sapiens*. But that situation was about to change.

Experts agree that the appearance of miniaturized stone tools in the archaeological record signals the advent of true projectile technology, for which lightness and ballistics are crucial. Such tools are too small to wield by hand. Instead they must have been mounted in slots grooved into bone or wood to create weapons capable of being launched at high speed and long distance. The oldest known examples of this so-called microlithic technology come from none other than Pinnacle Point. There, in a rock shelter known simply as PP5-6, my team found a long record of human occupation. Using a technique called optically stimulated luminescence dating, geochronologist Zenobia Jacobs of the University of Wollongong in Australia determined that the archaeological sequence in PP5-6 spans the time from 90,000 to 50,000 years ago. The oldest microlithic tools at the site date to around 71,000 years ago.

The timing hints that climate change may have precipitated the invention of this new technology. Before 71,000 years ago, the inhabitants of PP5-6 were making large stone points and blades from a type of rock called quartzite. Back then, as team member Erich Fisher of Arizona State has shown, the coastline was close to Pinnacle Point. And reconstructions of the climate and environment by Mira Bar-Matthews of the Geological Survey of Israel and Kerstin Braun, now a postdoctoral researcher at Arizona State, indicate that conditions were similar to the ones that prevail in the area today, with strong winter rains and shrubby vegetation. But around 74,000 years ago the world's climate began shifting to glacial conditions. The sea level dropped, exposing a coastal plain; summer rains increased, resulting in the spread of highly nutritious grasses and woodlands dominated by acacia trees. We think a large migration ecosystem in which grazing animals traveled east in the summer and west in the winter, tracking the rainfall and hence the fresh grass, developed on the formerly submerged coast.

Exactly why the denizens of PP5-6 began making small, light armaments after the climate shifted is unclear. But perhaps it was to pick off animals as they migrated across the new plain. Whatever the reason, the people there developed an ingenious means of making their tiny tools: turning to a new raw material—a rock called silcrete—they heated it with fire to make it easier to shape into small, sharp points. Only with the shift in climate that occurred could these early modern humans have had access to a sufficiently steady supply of firewood from the spreading acacia trees to make the manufacture of these heat-treated microlithic tools into an enduring tradition.

TINY STONE BLADES, or microliths, from Pinnacle Point in South Africa (*top*) show that humans invented projectile weapons by 71,000 years ago. They attached the microliths to wood shafts to form arrows or darts like those reconstructed here (*bottom*).

We do not yet know what kind of projectile technology these microliths were used for. My colleague Marlize Lombard of the University of Johannesburg in South Africa has studied somewhat later examples from other sites and argues that they represent the origin of the bow and arrow, given that damage patterns on them resemble those seen on known arrow tips. I am not totally convinced, because her study did not test the damage created by atlatls. Whether at Pinnacle Point or elsewhere, I think the simpler atlatl preceded the more complex bow and arrow.

I also suspect that like recent hunter-gatherers in Africa, whose lives were documented in ethnographic accounts, early *H. sapiens* would have discovered the effectiveness of poison and used it to increase the killing power of projectiles. The final killing moments of a spear hunt are chaos—pounding heart, heaving lungs, dust and blood, and the stink of sweat and urine. Danger abounds. An animal run to ground, fallen to its knees through exhaustion and blood loss, has one last trick: instinct screams for the beast to lurch to its feet one final time, close the gap and bury its horns in your guts. The short lives and broken bodies of Neandertals indicate that they suffered the consequences of hunting large animals at close range with handheld spears. Now consider the advantages of a projectile launched from afar and tipped with poison that paralyzes that animal, allowing the hunter to walk up and end the chase with little threat. This weapon was a breakthrough innovation.

FORCE OF NATURE

WITH THE JOINING of projectile weapons to hyperprosocial behavior, a spectacular new kind of creature was born, one whose

NEW SCENARIO

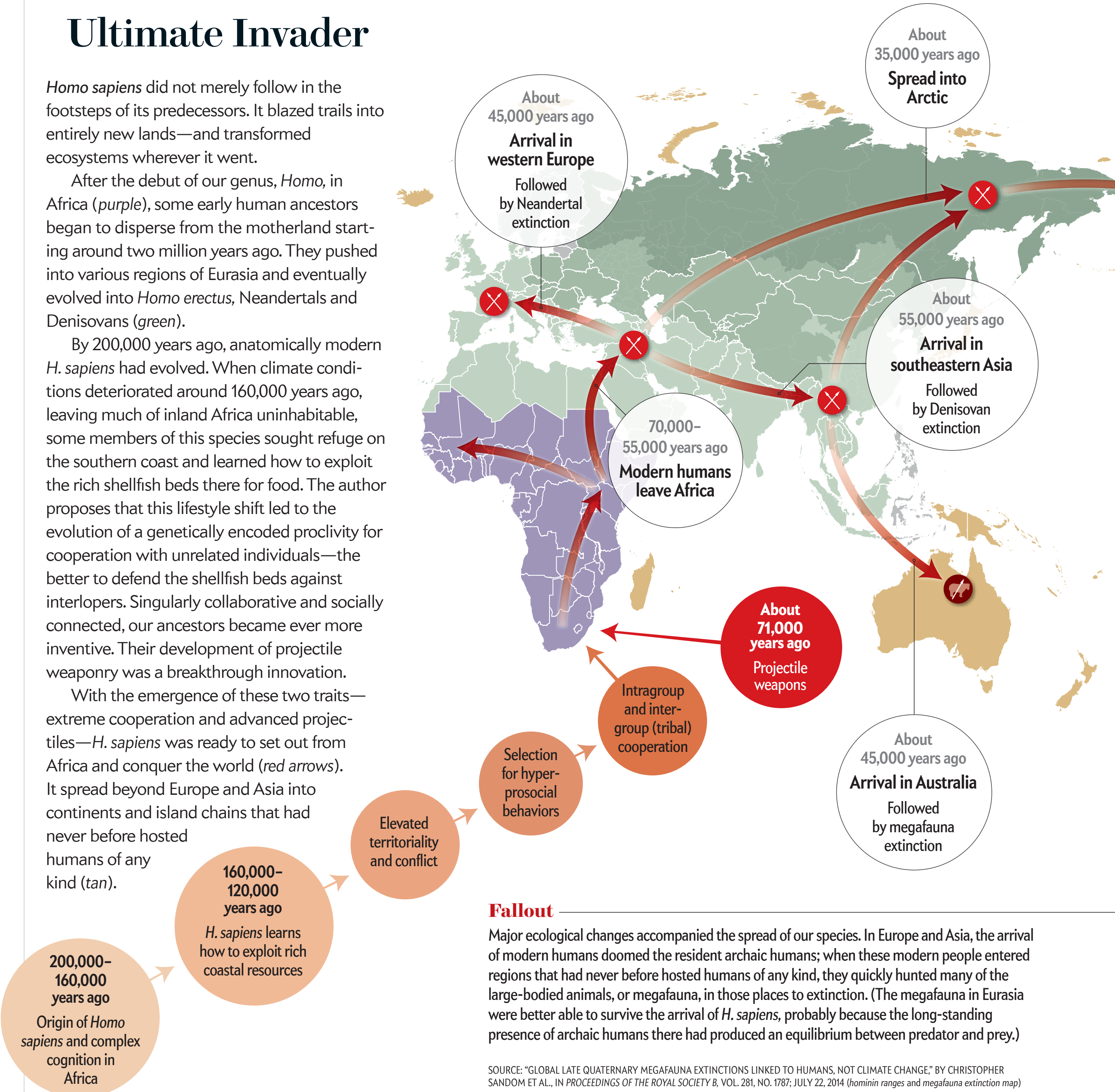
Ultimate Invader

Homo sapiens did not merely follow in the footsteps of its predecessors. It blazed trails into entirely new lands—and transformed ecosystems wherever it went.

After the debut of our genus, *Homo,* in Africa (*purple*), some early human ancestors began to disperse from the motherland starting around two million years ago. They pushed into various regions of Eurasia and eventually evolved into *Homo erectus,* Neandertals and Denisovans (*green*).

By 200,000 years ago, anatomically modern *H. sapiens* had evolved. When climate conditions deteriorated around 160,000 years ago, leaving much of inland Africa uninhabitable, some members of this species sought refuge on the southern coast and learned how to exploit the rich shellfish beds there for food. The author proposes that this lifestyle shift led to the evolution of a genetically encoded proclivity for cooperation with unrelated individuals—the better to defend the shellfish beds against interlopers. Singularly collaborative and socially connected, our ancestors became ever more inventive. Their development of projectile weaponry was a breakthrough innovation.

With the emergence of these two traits—extreme cooperation and advanced projectiles—*H. sapiens* was ready to set out from Africa and conquer the world (*red arrows*). It spread beyond Europe and Asia into continents and island chains that had never before hosted humans of any kind (*tan*).



Fallout

Major ecological changes accompanied the spread of our species. In Europe and Asia, the arrival of modern humans doomed the resident archaic humans; when these modern people entered regions that had never before hosted humans of any kind, they quickly hunted many of the large-bodied animals, or megafauna, in those places to extinction. (The megafauna in Eurasia were better able to survive the arrival of *H. sapiens,* probably because the long-standing presence of archaic humans there had produced an equilibrium between predator and prey.)

SOURCE: "GLOBAL LATE QUATERNARY MEGAFAUNA EXTINCTIONS LINKED TO HUMANS, NOT CLIMATE CHANGE," BY CHRISTOPHER SANDOM ET AL., IN *PROCEEDINGS OF THE ROYAL SOCIETY B,* VOL. 281, NO. 1787; JULY 22, 2014 (*hominin ranges and megafauna extinction map*)

SCIENTIFIC AMERICAN ONLINE View a slide show of images from the Pinnacle Point excavations at ScientificAmerican.com/aug2015/marean

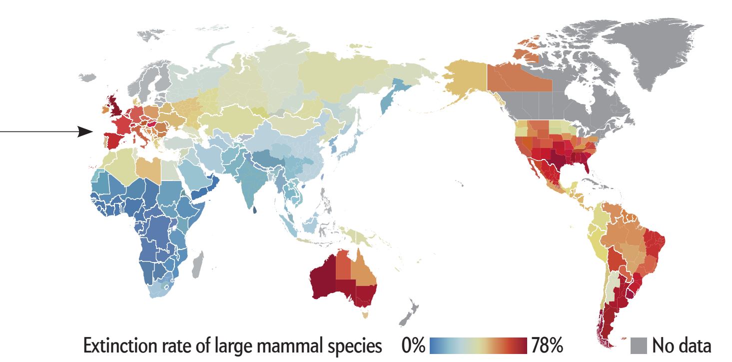
members formed teams that each operated as a single, indomitable predator. No prey—or human foe—was safe. Availed of this potent combination of traits, six men speaking six languages can put back to oar and pull in unison, riding 10-meter swells so the harpooner can rise to the prow at the headsman's order and fling lethal iron into the heaving body of a leviathan, an animal that should see humans as nothing more than minnows. In the same way, a tribe of 500 people dispersed in 20 networked bands can field a small army to exact retribution on a neighboring tribe for a territorial incursion.

The emergence of this strange brew of killer and cooperator may well explain why, when glacial conditions returned between 74,000 and 60,000 years ago, once again rendering large swathes of Africa inhospitable, modern human populations did not contract as they had before. In fact, they expanded in South Africa, flourishing with a wide diversity of advanced tools. The difference was that this time modern humans were equipped to respond to any environmental crisis with flexible social connections and technology. They became the alpha predators on land and, eventually, sea. This ability to master any environment was the key that finally opened the door out of Africa and into the rest of the world.

Archaic human groups that could not join together and hurl weapons did not stand a chance against this new breed. Scientists have long debated why our cousins the Neandertals went extinct. I think the most disturbing explanation is also the most likely one: Neandertals were perceived as a competitor and threat, and invading modern humans exterminated them. It is what they evolved to do.

Sometimes I think about how that fateful encounter between modern humans and Neandertals played out. I imagine the boasting tales Neandertals might have told around their campfires of titanic battles against impossibly huge cave bears and mammoths, fought under the gray skies of glacial Europe, barefoot on ice slick with the blood of prey and brother. Then, one day, the tradition took a dark turn; the regaling turned fearful. Neandertal raconteurs spoke of new people coming into the land—fast, clever people who hurled their spears impossible distances, with dreadful accuracy. These strangers even came at night in large groups, slaughtering men and children and taking the women.

The sad story of those first victims of modern human ingenuity and cooperation, the Neandertals, helps to explain why horrific acts of genocide and xenocide crop up in the world today. When resources and land get sparse, we designate those who do not look or speak like us as "the others," and then we use those differences to justify exterminating or expelling them to eliminate competition. Science has revealed the stimuli that trigger our hardwired proclivities to classify people as "other" and treat them horrifically. But just because *H. sapiens* evolved to react to scarcity in this ruthless way does not mean we are locked into this response. Culture can override even the strongest biological instincts. I hope that recognition of why we instinctively turn on one another in lean times will allow us to rise above our malevolent urges and heed one of our most important cultural directives: "Never again." SA



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Maps by Terra Carta

BIG GLASS: Mounted to the Gemini South telescope high in the Chilean Andes, GPI is a world-class instrument meant to see gas-giant exoplanets.

SPACE SCIENCE

IN SEARCH OF ALIEN JUPITERS

Two rival teams of astronomers are racing to capture unprecedented images of giant planets around other stars. What they find could change the future of planet hunting

By Lee Billings

Lee Billings is an associate editor at *Scientific American.* He is author of *Five Billion Years of Solitude: The Search for Life among the Stars* (Current/Penguin Group, 2013).

High in the remote Andes of central Chile, the night sky is so dark that the constellations are hard to see, swallowed up in swarms of fainter stars. The familiar yet alien view can be disconcerting, but something else troubles Bruce Macintosh when he looks up late one May evening in 2014. Even here, at 2,700 meters above sea level, he is still staring through an ocean of air, and the wind is rising. The stars overhead are twinkling a bit too much for his purposes.

Macintosh is here to look for other Earths—or, more precisely, for other Jupiters, which some scientists think are necessary for rocky, habitable, Earth-like planets to exist. He is not interested in finding planets like most astronomers do, watching for months or even years as subtle shifts in a star's motion or brightness gradually reveal the presence of an unseen world. He is after instant gratification: he intends to take actual pictures of remote planets, to see them as points of light circling their distant stars, to look on their gas-swirled faces across the gulf of light-years. Macintosh, an astronomer at Stanford University, calls this "direct imaging."

Besides the wind, there is another reason Macintosh is troubled: 600 kilometers to the north, on another arid Chilean peak, astronomer Jean-Luc Beuzit is trying to do the exact same thing. Beuzit, an astronomer at the Grenoble Institute of Planetology and Astrophysics in France, is Macintosh's friend—as well as his rival. Fate and funding have brought these men to the mountains at the same time to scour the heavens for planets, to learn whether our own is as common as dirt or cosmically rare.

Macintosh's tool of choice in this astronomical race is a multimillion-dollar car-sized complex of optics and sensors called the Gemini Planet Imager (GPI). It is mounted to the immense eight-meter mirror of the Gemini South telescope, a polished disk of silvered glass that would take up an eighth of a regulation basketball court. Macintosh and other astronomers pronounce the instrument's acronym "gee pie," as if they are exclaiming about pastry. Beuzit's answer to GPI is an even bigger, minivan-sized collection of gadgets called SPHERE, for Spectro-Polarimetric High-contrast Exoplanet REsearch instrument. SPHERE is mounted

IN BRIEF

Astronomers know of thousands of planets orbiting other stars but have imaged only a handful. They have discovered and studied all the rest mostly through indirect measurements.

Imaging a planet allows researchers to learn more about its composition, climate and prospects for life. But imaging is hard because planets are faint and close to much brighter stars.

Imaging Earth-like planets is beyond the reach of current telescopes. A new generation of instruments is now taking pictures of bigger, brighter worlds that resemble our own Jupiter.

These new instruments will help scientists learn how giant planets form and how they sculpt their surroundings, preparing the way for future facilities to take pictures of alien Earths.

PRECEDING PAGES: COURTESY OF GEMINI OBSERVATORY/AURA; THIS PAGE: COURTESY OF G. HÜDEPOHL/EUROPEAN SOUTHERN OBSERVATORY

HIGH AND DRY: SPHERE, another planet imager, seeks alien Jupiters from the Very Large Telescope in Chile's barren Atacama Desert.

on another eight-meter telescope, at the European Southern Observatory's Very Large Telescope array. Both projects have been in development for more than a decade but debuted within months of each other. From their remote mountaintop perches, they are surveying mostly the same stars, seeking to be the first with breakthrough snapshots of alien Jupiters.

Of the more than 5,000 worlds discovered orbiting other stars over the past two decades, scarcely any have actually been directly imaged. Taking pictures is hard because even the largest, least inhabitable planets are still very dim and appear very close to their far brighter suns, as seen from far away. Take a picture of a planet—even if it is a small smudge of pixels—and you can learn a lot about that world's composition, climate and possibilities for life. GPI's and SPHERE's quest for Jupiter-like worlds is the state of the art; humans have yet to build telescopes big and sophisticated enough to distill the faint light of an alien Earth from the overpowering glare of an adjacent star. But when and if they do, those facilities will almost certainly use instruments developed from these two projects.

In astronomy, as in everyday life, seeing is believing. Although direct imaging can be fiendishly difficult, it can also be much faster than today's dominant planet-detection techniques, potentially delivering discoveries through pictures that take hours or days to obtain rather than through months or years of painstaking analysis on arcane stellar data sets. Which is why, in this race to take the first pictures of alien Jupiters, it is not a stretch to say that every minute counts.

THE TORTOISE AND THE HARE

TIME WEIGHS HEAVILY on Macintosh as he works in Gemini South's control room late that night in May 2014. He has a boyish face, with a crescent of brown hair and lively eyes that peer from behind thick glasses. He is running on Diet Coke and adrenaline, still jet-lagged from a string of connecting flights from California to Chile. One of his shoes is untied, and a faint smell of smoke wafts through the air from a forgotten dinner of frozen pizza, now carbonized in a nearby toaster oven. As he gazes at a bank of computer screens monitoring GPI's vitals, it seems only his body is in the room—his mind is elsewhere, in the adjacent dome housing the eight-meter telescope, following beams of light bouncing through the innards of his instrument.

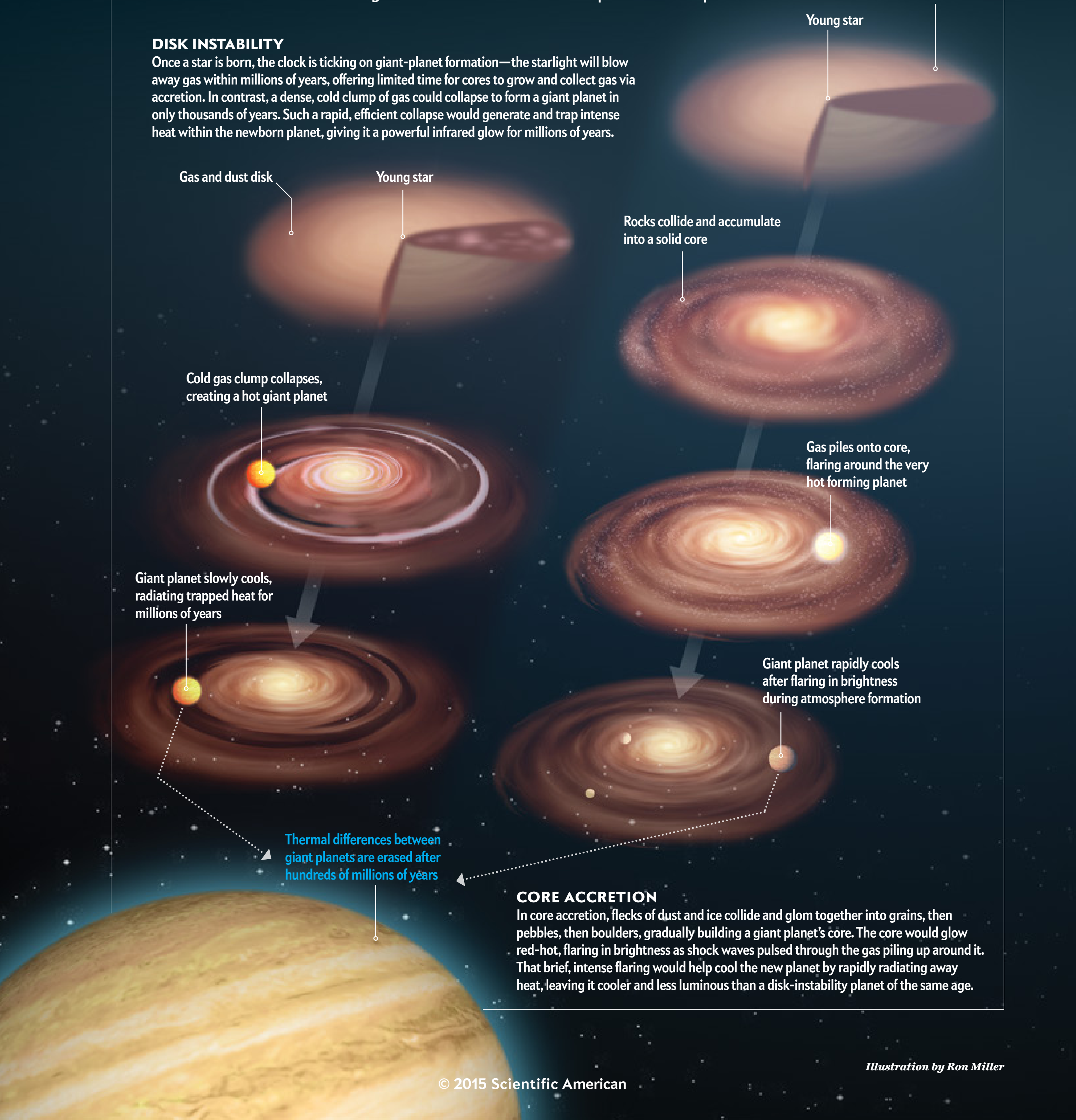
Before GPI can start finding new planets, it first must go through "commissioning," an extended sequence of tests and calibrations that started in late 2013 and, by this time in May 2014, is in the final stages. The work is tedious and unglamorous—no one has ever won a prize for making sure an instrument operates prop-

Birth of a Gas Giant: Two Scenarios

Planets form from the same disks of gas and dust that give birth to suns. A process called core accretion can make giant planets from the bottom up, as tiny objects stick together to gradually build bigger ones, assembling a large core that sweeps up a thick atmosphere. But a faster, top-down pathway called disk instability exists, in which clumps of gas collapse directly into planethood. On average, young giants made by core accretion should be cooler than those made by disk instability. By taking the temperatures of young giant planets via infrared imaging, GPI and SPHERE could reveal whether most giants are built from the bottom up or from the top down.

DISK INSTABILITY

Once a star is born, the clock is ticking on giant-planet formation—the starlight will blow away gas within millions of years, offering limited time for cores to grow and collect gas via accretion. In contrast, a dense, cold clump of gas could collapse to form a giant planet in only thousands of years. Such a rapid, efficient collapse would generate and trap intense heat within the newborn planet, giving it a powerful infrared glow for millions of years.



CORE ACCRETION

In core accretion, flecks of dust and ice collide and glom together into grains, then pebbles, then boulders, gradually building a giant planet's core. The core would glow red-hot, flaring in brightness as shock waves pulsed through the gas piling up around it. That brief, intense flaring would help cool the new planet by rapidly radiating away heat, leaving it cooler and less luminous than a disk-instability planet of the same age.

Illustration by Ron Miller

erly. In a race measured in minutes, GPI has a quarter-million-minute lead over SPHERE, which, by this same time, has only just begun the commissioning process. That is small comfort to Macintosh, however, because SPHERE has a more capable suite of instruments and more guaranteed telescope time than GPI, which should allow SPHERE to observe a greater number of stars in a larger field of view at higher spectral resolutions across a wider range of wavelengths. In other words, even though GPI is out front, like the hare in Aesop's famous fable, SPHERE could still come from behind, tortoiselike, and find the sought-after planets first.

The twinkling of the stars comes from turbulence in the atmosphere, which has pushed the GPI team behind schedule. Waiting for the wind to die down, Macintosh tells me stories from years ago, when he, Beuzit, and other high-ranking members of the GPI and SPHERE teams would carouse at astronomy conferences around the world, their future conflict far from their minds. Those times are long past. "We'd get together, drink heavily and trade stories," Macintosh says. "Even now, they aren't really the enemy—the clouds are the enemy. And the wind."

After half an hour, the winds have abated. "Okay, let's look at HD 95086," Macintosh says, spinning in his chair to address the dozen or so team members in the room. They spring to action, keying commands into the computers controlling the telescope in the dome next door. Within moments the telescope has slewed to the target, a bluish-white dwarf star 300 light-years from Earth, in the constellation Carina. HD 95086 is a young star in astronomical terms—only about 17 million years old—and bears a giant planet five times more massive than Jupiter, orbiting approximately twice as far out as Pluto. Earlier, less capable direct-imaging projects have seen this planet before—the team will calibrate GPI by comparing its new images with the earlier results.

Like all the worlds that GPI seeks, this particular planet has scarcely cooled at all since its formation. It glows brightly in infrared light. In terms of brightness, most planets are millions or billions of times fainter than their stars, flecks of dust on the cusps of thermonuclear fireballs. Young Jupiters are different. They are more like red-hot embers cooling far from a campfire, which is precisely why GPI or SPHERE has any hope of seeing them and learning how exactly they formed and evolved.

JUPITER'S SECRET ORIGINS

AMONG EXPERTS, it is an embarrassing open secret that no one really knows how the largest object orbiting our sun came to be. But the experts desperately want to find out because Jupiter and other giant planets are the architects of planetary systems, shaping all that surrounds them.

Most of the known giant planets around other stars are not really like Jupiter at all. Many exist in scorching half-week orbits alien to anything in our own solar system. The prevailing theory is that these hellish worlds were born much farther out, only to spiral down to hug their suns because of gravitational interactions with other planets or flows of gas. That migration would be bad news for habitability—along the way, the gravitational field of an in-spiraling giant planet would most likely toss any small, rocky planets out into the interstellar dark or down into the fires of its star. Such giant worlds are too close to their stars to be directly imaged with today's technology.

Like its much hotter exoplanetary cousins, Jupiter probably also migrated early in its life, but for reasons unclear, its migration was only temporary and did not bring the giant planet within spitting distance of the sun. Instead it perhaps ventured about as far in as present-day Mars, before retreating back to the outer solar system, where it has stayed ever since. And although the motions of a giant planet can sabotage a planetary system's habitability, in Jupiter's case they seem to have made our solar system a more hospitable place. At the least, Jupiter's peregrinations are thought to have flung water-rich comets and asteroids down to our already formed planet, delivering life-giving oceans. At most, Jupiter's plunge into the inner solar system might have even cleared out other preexisting planets, allowing Earth to form in the first place.

Most planets are far fainter than their stars, flecks of dust around nuclear fireballs. Young Jupiters are different. They are more like embers cooling far from a campfire, which is why GPI or SPHERE has any hope of seeing them.

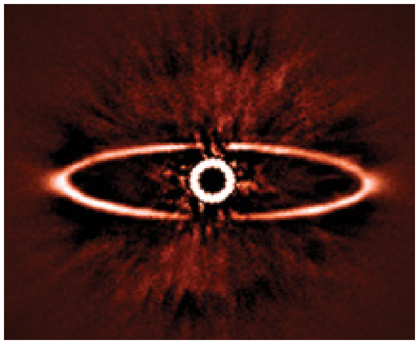
Even so, what Jupiter gives, it could take away. Millions of years from now, Jupiter may pummel our planet again with more giant asteroids or comets, generating cataclysmic impacts that would boil off our oceans and steam-cook our biosphere.

All these details, to some degree, can be traced to the nature and timing of Jupiter's mysterious formation. This much is certain: just more than four and a half billion years ago, a cold cloud of gas and dust collapsed to form our sun. The remnants of the cloud that did not fall into our nascent star spun out into a disk, and from this material planets formed. Rocky worlds, being relatively small, are easy to assemble in a bottom-up process called core accretion, where colliding rocks gradually glom together over as much as 100 million years. Most researchers suspect Jupiter formed in the same way. But to do so, it would have had to form far faster, building up Earth-sized cores in perhaps 10 million years, time enough to sweep up huge atmospheres before the gassy feedstock is blown away by the intense light of a young star.

Another possibility exists. Giant planets could also form much like stars do in a top-down process called disk instability. In this scenario, something like Jupiter would achieve planethood through the direct, rapid collapse of a cold, overdense clump of gas and dust in the outer region of a circumstellar disk. It is almost impossible to distinguish between these two scenarios for Jupiter today because essentially all the evidence is literally buried below the giant planet's dense, thick atmosphere.

Fortunately, there is another way to test whether giant planets form from the bottom up or the top down: you can take their temperatures. A top-down formation directly from a collapsing clump of gas would happen so quickly that an enormous amount of heat would be trapped within the planet. A bottom-up formation would instead produce giant planets that, though still initially red-hot, would be relatively cooler. "As more and more gas falls onto a rocky core, it's impeded by the gas below it, by the atmosphere forming around the core," says GPI collaborator Mark Marley, whom I speak to later, a planet-formation theorist at the NASA Ames Research Center who helped to model the process. "A shock develops as the gas slows down, and most of the energy of that infalling gas radiates out, which flash-cools the forming planet. So when you stop dumping gas on, the planet is much cooler than it would've been from a direct collapse."

Thus, a giant planet's temperature is effectively a memory of its birth. The older the planet gets, the more it cools, and the more its memory fades. Some four and a half billion years old, Jupiter long ago forgot how it formed. But giant planets younger than a few hundred million years—the very planets GPI and SPHERE are trying to image in the infrared—should still have their thermal memories intact. Surveying hundreds of bright, youthful nearby stars, both projects may probe the temperatures and histories of dozens of giant planets, unraveling the secret of their formation and shedding light on how habitable systems like our own came to be.



UNBLINKING EYE: **Light from the star HR 4796A is filtered out in this SPHERE image, revealing a faint ring of dust, perhaps sculpted by an unseen planet.**

COURTESY OF JEAN-LUC BEUZIT ET AL./EUROPEAN SOUTHERN OBSERVATORY/SPHERE CONSORTIUM

IMAGING AN ALIEN JUPITER

AS THE GPI TEAM PREPARES to observe HD 95086, a monochrome circle materializes on one of Macintosh's screens. It seems to contain a heavily pixelated fluid, like a digitized close-up of a rushing river or an untuned television awash with static.

"You're looking at the wind," Macintosh says. "That's starlight shining through atmospheric turbulence and falling on a detector that drives our adaptive optics." Adaptive optics are computer-controlled deformable mirrors that change their shape hundreds or even thousands of times a second to combat atmospheric distortions, allowing astronomers to capture images of celestial objects that rival those available from space telescopes. With a few keystrokes and verbal commands to his team, Macintosh powers up GPI's adaptive optics. Mounted underneath the eight-meter telescope, GPI's two deformable mirrors—an off-the-shelf glass "woofer" and a smaller, custom-built "tweeter" packed with more than 4,000 actuators—are now rippling and curling in synchrony, matching each transient light-smearing pocket and flow of overlying air with a corresponding dip or spike in their surfaces, sculpting the rays of starlight back to near perfection. The result seems magical: the turbulent circle on Macintosh's screen becomes smooth and placid, as if the atmosphere overhead has suddenly disappeared. HD 95086 is now a brilliant glare on-screen. There is no sign of a planet.

To reveal the star's known planet, Macintosh engages another device, a coronagraph, that strips out most of the starlight: the light encounters a series of masks that filter out 99 percent of the photons. The ones that make it through are focused and aimed at a mirror with a central hole polished to atomic-scale smoothness. "The star's light falls down the hole," Macintosh explains, whereas a planet's light will instead bounce off the mirror and go deeper into the instrument, reaching a supercooled spectrograph that splits the light into its constituent wavelengths (or colors).

The picture on-screen is now a lumpy halo of white light surrounding a deep, central shadow where HD 95086 should be. The lumps—called speckles—are formed from unwanted starlight that leaks through the coronagraph. Speckles can obscure a planet in GPI's images or even masquerade as one. To distinguish between speckles and planets, the team takes a sequence of exposures at various infrared wavelengths. "The separation between a star and a speckle is proportional to the wavelength of light in an image," says GPI's project scientist James Graham, a professor at the University of California, Berkeley, as we stare at the screen. At shorter, bluer wavelengths, a speckle will appear closer to a star; at longer, redder wavelengths, that same speckle will appear farther away, Graham explains. "So when you see the whole [wavelength] sequence, the speckles will move. A planet won't."

Macintosh scrolls back and forth through the stacked exposures like frames in a movie, and the halo seems to breathe, expanding and contracting as all the lumps move in unison. All the lumps, that is, save for one: a lone, fixed dot of planetary light fished from a sea of stellar speckles. In less than half an hour, we have gone from seeing only the wind to staring at a distant world around another star. Further analysis of the planet's spectrum from GPI data hints that the planet is extremely red, perhaps the result of an excess of light-scattering dust in its upper atmosphere. It is a small but thrilling detail to learn about a world that is 300 light-years away.

Not all targets are so difficult to see; closer, brighter stars can give up some of their secrets far more readily. Earlier, the GPI team had needed only a single 60-second exposure to capture an image of Beta Pictoris b, a hot, young giant planet 63 light-years from Earth that orbits its star at almost twice the Jupiter-sun distance. The ease of seeing that planet suggests that direct imaging, at last, is becoming routine: a slightly older direct imager on Gemini South had previously taken a similar image of Beta Pictoris b, although it required more than an hour of observation and extensive postprocessing. The new images allowed the GPI team to estimate the orbit of Beta Pictoris b with higher precision than ever before, revealing that in 2017 it might transit across the face of its star as seen from Earth—a rare alignment that would be a boon for scientists seeking to learn more about the distant giant.

In the remaining hours before sunrise, the GPI team images binary stars, faint debris disks, and even Saturn's moon Titan, peering down through its thick, hazy, hydrocarbon-filled atmo-

SCIENTIFIC AMERICAN ONLINE Read more about the science and technology of planet imaging at ScientificAmerican.com/aug2015/alien-jupiters

sphere to its blotchy surface. Near dawn, when the glow of the approaching sun begins filtering up from the horizon, Macintosh leans far back in his chair and sighs, exhausted but satisfied.

On the final night of the six-day run, the GPI team finds its first planet, orbiting a 20-million-year-old star at twice the Jupiter-sun distance. Macintosh is not the first to notice it—Robert de Rosa, a postdoctoral student at U.C. Berkeley, spies the flickering dot while looking over another teammate's shoulder at some otherwise unremarkable GPI images. Subsequent observations show it to be between two and three times Jupiter's mass, with a methane-filled atmosphere hot enough to melt lead. The planet is 100 light-years from Earth, but it is the closest thing to Jupiter astronomers have ever seen.

"This is the first planet anyone has ever found that looks like a warm version of Jupiter rather than a very cool star," Macintosh says. "This planet may be young enough to still 'remember' its formation process. With enough observations we could pin down its mass and age and figure out whether it formed from the bottom up, like we think Jupiter did, or from the top down, like a star."

When Macintosh tells me, he also vows me to secrecy until the GPI team can write and submit a paper. "SPHERE could very easily see this, too," he says. "We don't know if they've looked yet at the same star. We are all nervous we'll get scooped."

FIRST LIGHT FOR THE FUTURE

SHORTLY AFTER DAWN, I leave Gemini South, catch an airplane north, rent a car and speed on a lonely highway through Chile's high, dry Atacama Desert, traveling more than 600 kilometers door-to-door to reach SPHERE before night falls. I arrive at SPHERE's observatory, the Very Large Telescope, just after sunset. In a cramped control room Beuzit, the project's leader, is marshaling his troops as the commissioning begins. The astronomers are hunched over computer screens, quietly conversing in French, German and English, trying to ignore the cameras and boom microphones of a visiting documentary film crew. Beuzit, with his unkempt dark hair and beard, looks a bit like the late film director Stanley Kubrick. He drifts from station to station, sipping espresso, pausing here and there to listen and advise. A recently emptied bottle of Laurent-Perrier champagne sits on a nearby bookshelf, "SPHERE 1st Light" scrawled in black marker on its label.

SPHERE performs admirably during commissioning, producing gorgeous pictures of a variety of celestial targets, including a faint dust ring around HR 4796A, an eight-million-year-old star 237 light-years from Earth in the constellation Centaurus [*see illustration on opposite page*]. Later, as I gaze at the ring with the blotted-out star at its center, I feel like I am being watched—it looks like an enormous eye, staring across the interstellar gulf. But despite those pretty pictures, on the night of my visit, SPHERE is not quite ready to go discover new planets, Beuzit tells me. Not all is well with the system's adaptive optics: some of the mirror-bending actuators on SPHERE's €1-million, 1,377-element deformable mirror are failing, and no one on the team can figure out why. The ultimate solution, Beuzit says, may be to replace the entire mirror with a new one using different actuator technology. Even so, he is optimistic that SPHERE and GPI alike will each meet and exceed their goals. In the meantime, commissioning must go on—it concluded earlier this year, generating its own first batch of early science observations, producing images of several previously imaged planetary systems.

When I ask him about SPHERE's rivalry with GPI, Beuzit's first response is only to smile and sip his coffee. After a moment, he speaks carefully. "Once we both start discovering new planets, no one will remember who was first on-sky," Beuzit says. "I'm not saying that we won't compete and fight, us and the Americans. But Bruce Macintosh and I have known each other for 15 years, and we both know how hard this is. We celebrate our successes and share our difficulties to improve both of our systems, to prepare the way for the next generation of observatories and imagers."

"We are entering a new age as all these facilities come online at almost the same time," says Dimitri Mawet, a professor at the California Institute of Technology and at the time a SPHERE principal instrument scientist. "We're going to discover many wonderful things, but we're also going to significantly push the adaptive optics technology forward. That will be fundamental for the next generation of telescopes, which will require these kinds of controls just to keep their huge mirrors aligned."

One of those new telescopes is being planned just 20 kilometers to the northeast of SPHERE, on the 3,000-meter peak of Cerro Armazones. Shortly after my visit, explosives blast off the peak's top, clearing ground for the construction of the European Extremely Large Telescope, one of three supersized observatories slated to debut in about a decade. Paired with the unprecedented light-gathering power of such an observatory's gargantuan 30- or 40-meter mirror, a system similar to SPHERE or GPI would be able to image not only self-luminous Jupiters but also cooler, 1,000 times fainter, potentially habitable planets orbiting the sun's nearest neighboring stars. A dedicated direct-imaging mission in space could then probe them even further, seeking signs of life. Provided, that is, such worlds are even there to see. The prospect of getting those images, glimpsing alien Earths, is what motivates many of the people behind projects such as GPI and SPHERE.

Macintosh had said as much during our conversations at Gemini South: "I see everything we're doing now as steps along the road toward a picture of another Earth. Someday we will have that picture. If we finally get results on the fraction of small, rocky planets that include really relevant things—which ones have oceans, atmospheric oxygen, and so on—and that number turns out to be very tiny, well, that's probably pretty important. It may make no practical difference to the progression of our civilization for a very long time, but philosophically, being able to say that 'ours is the only place like this within 1,000 light-years,' maybe that would cause us to try a little harder not to screw it up." SA

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scientificamerican.com/magazine/sa

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NEUROSCIENCE

HIDDEN HEARING LOSS

Jackhammers, concerts and other common noisemakers may cause irreparable damage to our ears in unexpected ways *By M. Charles Liberman*

FOOTBALL FANS OF THE SEATTLE SEAHAWKS AND THE KANSAS CITY CHIEFS ROUTINELY compete at home games to set the Guinness World Record for the noisiest stadium. On October 1, 2014, the Chiefs hit the latest peak: 142.2 decibels (dB). That level is like the painful, blistering roar of a jet engine at 100 feet—a typical example that hearing experts give for a noise that is more than loud enough to cause hearing damage. After the game, the fans were ecstatic. They reveled in the experience, noting the ringing in their ears or the feeling that their eardrums were about to explode. What was happening inside their ears was far from wonderful, however.

A hearing test, if administered before and immediately after the game, might have shown a marked deterioration. The softest sound that a fan could have heard before kickoff—say, whispered words—might no longer be detectable by halftime. The thresholds for hearing might have risen by as much as 20 to 30 dB by the final whistle. As the ringing in fans' ears subsided over the course of a few days, the output of the hearing test, an audiogram, might well return to baseline, as the ability to hear faint sounds returned.

Scientists long thought that once thresholds returned to normal, the ear must have done so as well. Recently my colleagues and I have shown that this presumption is not true. Exposures that lead to only a temporary rise in thresholds can, nonetheless, cause immediate and irreversible damage to fibers in the auditory nerve, which conveys sound information to the brain. Such damage may not affect the detection of tones, as shown on the audiogram, but it can hamper the ability to process more complex signals. This newly recognized condition is called hidden hearing loss because a normal audiogram can hide the nerve damage and the hearing impairment associated with it.

As a person continues to abuse their ears, the toll on the nerve fibers can mount. In fact, such damage may contribute to the gradual deterioration in the ability of the middle-aged and elderly to discriminate the subtleties of speech. Hid-

BRIAN STAUFFER

den hearing loss, however, is by no means confined to older adults. The latest research suggests that it is occurring at ever younger ages in industrial society because of greater exposure to loud sounds, some avoidable, some not.

A SENSORY MARVEL

THE VULNERABILITY of the ear stems from its awe-inspiring sensitivity, which allows it to function across a vast range of sound levels. Our ability to just make out a quiet sound at frequencies near 1,000 oscillations per second, or 1,000 hertz (Hz)—in other words, the threshold at which we can perceive that sound—is defined as zero decibels. Using this logarithmic measure, each 20-dB increase in sound level corresponds to a 10-fold increase in the amplitude of the sound waves. At 0 dB, the bones of the middle ear, whose vibrations drive the hearing process, move less than the diameter of a hydrogen atom. At the other extreme, such as the pain-inducing levels of more than 140 dB at the record-setting Chiefs game, the ear is forced to deal with sound waves that are 10 million times greater in amplitude.

Hearing begins as the outer ear funnels sound waves through the ear canal to the eardrum, which vibrates and sets the bones of the middle ear in motion. The resulting vibrations then make their way to the inner ear's fluid-filled tube, the cochlea—the location of hair cells that occupy a spiraling strip of tissue called the organ of Corti. These cells get their name from hairlike protrusions known as stereocilia that extend in bundles from one end of the cells. Hair cells most sensitive to low frequencies lie at one end of the cochlear spiral, and those most sensitive to high frequencies lie at the other end. As sound waves bend the "hairs," these cells convert vibrations to chemical signals, emitting a neurotransmitter molecule—glutamate—at the other end, where the hair cells form synapses with the fibers of the auditory nerve.

At the synapse, the glutamate released from a hair cell crosses a narrow cleft to bind to receptors on the end, or terminal, of an auditory nerve fiber. Each terminal is at one end of a nerve cell that extends a long fiber, an axon, to its other end in the brain stem. Glutamate bound to nerve fibers triggers an electrical signal that travels the entire length of the auditory nerve to the brain stem. From there the signals move through a series of parallel neural circuits that traverse various regions—from the brain stem to the midbrain and thalamus—and finish their journey at the auditory cortex. Together this complex circuitry analyzes and organizes our acoustic environment into a set of recognizable sounds, whether it be a familiar melody or the wail of a siren.

Hair cells come in two types, termed outer and inner. Outer hair cells amplify the sound-induced motions in the inner ear, whereas inner hair cells translate these motions into the chemical signals that excite the auditory nerve. The inner cells are most directly responsible for what we think of as "hearing" because 95 percent of auditory nerve fibers form synapses only with inner hair cells. Why so few fibers connect the outer hair cells to the brain remains a mystery, but it has been theorized that the fibers connected to outer hair cells may be responsible for the pain that we all suffer when the loudness of a sound wave approaches 140 dB.

Historically hearing loss has been assessed mainly by audiograms. Ear doctors have long known that workers pounding sheet metal into boilers often had permanent hearing loss for tones in the middle-frequency region. Audiograms record our ability to detect tones at octave-frequency intervals: for example 250, 500, 1,000, 2,000, 4,000 and 8,000 Hz. In the early stages of noise-induced hearing loss, the audiogram exhibits what is called the boilermaker's notch, an inability to detect sounds in the middle frequencies of the human hearing range.

In the 1950s and 1960s epidemiological studies of workers in noisy factories showed a clear relation between length of employment and a decline in hearing acuity. The initial deficit near 4,000 Hz tended to spread to other frequencies over time. Many older workers lost hearing entirely above 1,000 or 2,000 Hz. Such high-tone loss causes a severe hearing impairment because much of the information in speech is in the frequency range that has become unresponsive.

Human studies such as these inspired the federal government in the 1970s to establish noise guidelines to limit workplace exposures. Today several federal agencies regulate noise levels on the job, including the National Institute for Occupational Safety and Health and the Occupational Safety and Health Administration, and different agencies suggest different limits. The lack of precise agreement reflects the challenges in assessing noise-damage risk. The problems are twofold. First, there are enormous individual differences in noise susceptibility: there are what might be described as "tough" ears and "tender" ears. That means regulators must choose what percentage of the population they want to protect and what level of hearing loss is acceptable. The other problem is that the effects of noise on hearing result from a complex combination of duration, intensity and frequency of sounds to which a person is exposed.

Currently OSHA mandates that sound levels not exceed 90 dB for an eight-hour day. The risk of noise damage above 90 dB is roughly proportional to the total energy that is delivered to the ear (duration multiplied by intensity). For each additional 5 dB above the eight-hour standard, OSHA guidelines recommend a halving of exposure time—in other words, a worker should not be exposed to 95 dB for more than four hours daily or to 100 dB for more than two hours a day. By these measures, the 142-dB-plus exposure of football fans vying for the Guinness noise record would exceed OSHA guidelines in around 15 seconds. Of course, OSHA does not regulate noise levels for fans at football games or even for U.S. farms, where teenagers driving tractors and combines all day are at serious risk of hearing loss.

For the past 60 years hearing special-

IN BRIEF

Conventional wisdom holds that loud noises cause muffled sound or ringing in the ears, but the ears soon recover.

Elevated noise levels can produce permanent damage to auditory nerve fibers that carry sound into the brain.

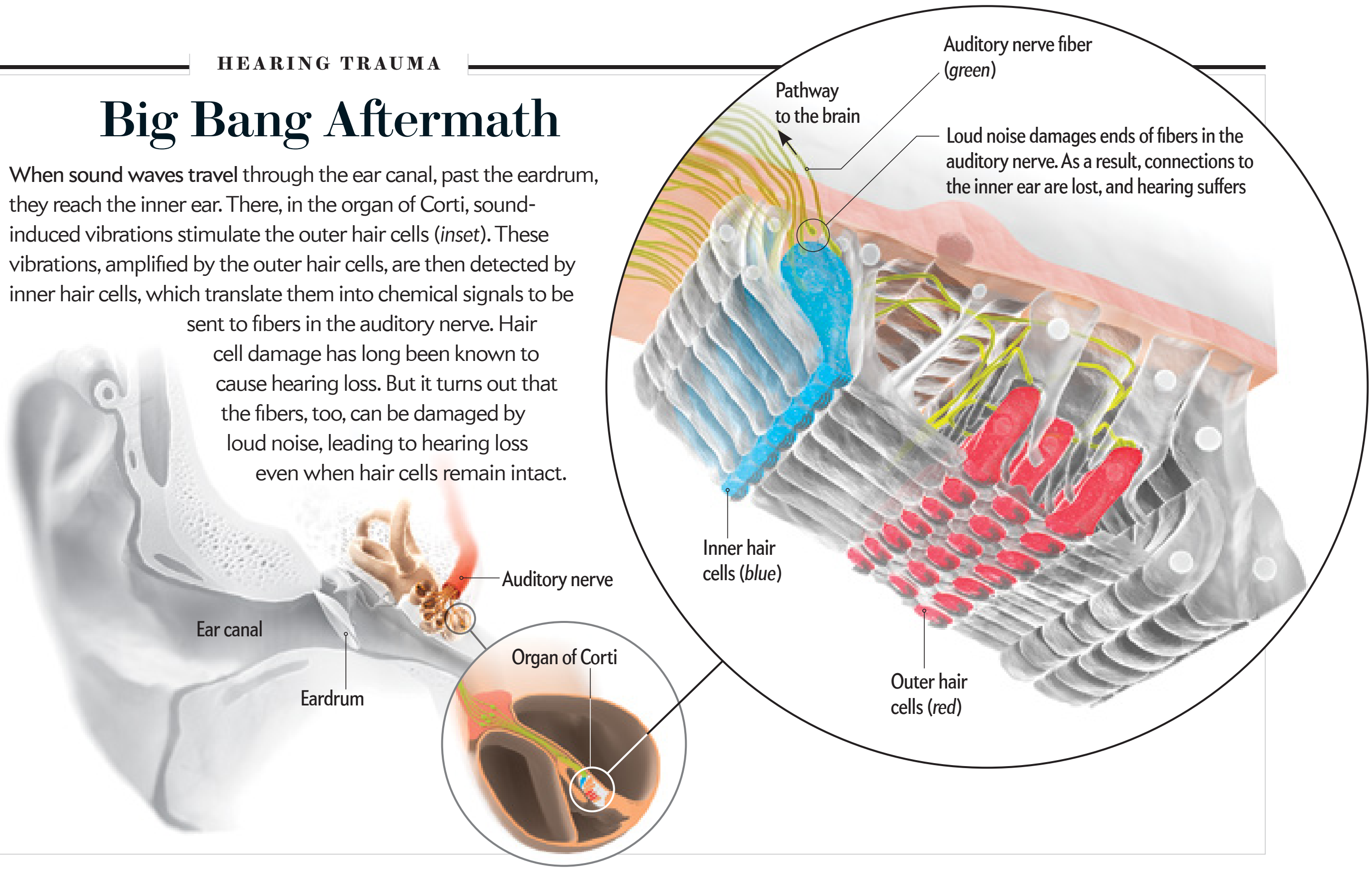
Hidden hearing loss that results may allow someone to hear sounds without making out what a speaker is saying.

A drug that lets the damaged nerve fibers recover may be one solution to this ubiquitous problem.

HEARING TRAUMA

Big Bang Aftermath

When sound waves travel through the ear canal, past the eardrum, they reach the inner ear. There, in the organ of Corti, sound-induced vibrations stimulate the outer hair cells (*inset*). These vibrations, amplified by the outer hair cells, are then detected by inner hair cells, which translate them into chemical signals to be sent to fibers in the auditory nerve. Hair cell damage has long been known to cause hearing loss. But it turns out that the fibers, too, can be damaged by loud noise, leading to hearing loss even when hair cells remain intact.



ists have assumed that routine readings of an audiogram reveal everything we need to know about noise-induced damage to hearing. Indeed, the audiogram will show if there has been damage to the inner ear's hair cells, and investigations from the 1940s and 1950s revealed that hair cells were among the most vulnerable cells in the inner ear to acoustic overexposures.

Experiments in animals, some performed in our laboratory, have shown that outer hair cells are more vulnerable than inner ones, that hair cells in the section of the cochlea that detects high-frequency tones are more vulnerable than those in the low-frequency region, and that, once lost, hair cells never regenerate. Even before the cells degenerate, loud noise can damage the bundles of stereocilia atop the cells, and this damage is also irreversible. When damage to or death of hair cells occurs, hearing thresholds are elevated—the radio must be turned up, or a colleague across the table must raise his or her voice.

More incisive study of cochlear damage in humans has been hampered by the fact that the tiny hair cells cannot be biopsied safely or imaged in a living individual with any existing technique. Damage associated with noise-induced hearing loss in humans has been studied only in people who have donated their ears for scientific study after death.

In part because of these limitations, the question of whether hearing loss is unavoidable in the aging process—or whether it is a consequence of repeated exposure to the clamor of modern life—continues to puzzle hearing scientists. A tantalizing hint came from a study in the 1960s, in which researchers sought out groups living in uniquely quiet environments, such as the Mabaan tribe in the Sudanese desert. Hearing testing was significantly better in Mabaan men, from 70 to 79 years old, compared with a group of American men of the same age. Of course, these studies cannot tease out other differences between an average American and the typical Mabaan, such as those related to genetic background or diet.

DEEP DAMAGE

RECENT INVESTIGATIONS by my colleagues and me into the effects of noise on hearing have added a sobering new dimension to our understanding of the dangers of acoustic overexposure. Scientists and clinicians have long known that some of the hearing impairment from noise exposure is reversible and that some is not. In other words, at times hearing thresholds return to normal a few hours or days after an exposure—other times recovery will be incomplete, and the higher threshold will persist forever. Hearing scientists used to think that if the threshold sensitivity recovered, the ear had completely recovered. We now know that this is not true.

The loud pop of Fourth of July firecrackers or the roar of the crowd at a football game not only affects the hair cells, it also damages the auditory nerve fibers. We and others showed in the 1980s that overly loud noise causes damage to the terminals of the nerve fibers where they form synapses with hair cells. The swelling and eventual rupture of the terminals probably occur in response to excess release of the signaling molecule glutamate from the overstimulated hair cells. Indeed, too much glutamate release anywhere in the nervous system is toxic. The conventional wisdom had been that these noise-damaged fibers must recover or regenerate after intense noise exposure because auditory thresholds can return to normal in ears that showed massive nerve swelling immediately after exposure.

In my lab, we were skeptical that such

Illustration by Bryan Christie

badly damaged synapses could regenerate in the adult ear. We also knew that noise-induced nerve damage would not necessarily be reflected in the standard testing because animal studies dating back to the 1950s showed that loss of auditory nerve fibers, without loss of hair cells, does not affect the audiogram until the loss becomes catastrophic, greater than 80 percent. It appears that you do not need a dense population of nerve fibers to detect the presence of a tone in a quiet test booth. By analogy, take a digital image of a group of people and sample it repeatedly, each time at a lower resolution. As you decrease the pixel density, the details of the image become less clear. You can still tell there are people in the picture, but you cannot tell who they are. Similarly, we hypothesized, diffuse loss of neurons need not affect your ability to detect a sound, but it could easily degrade understanding of speech in a noisy restaurant.

When we began investigating noise-induced nerve damage in the 1980s, the only way to count the synapses between auditory nerve fibers and inner hair cells was with a technique called serial-section electron microscopy, a highly laborious process requiring roughly a year of work to analyze the nerve synapses on only a few hair cells from one cochlea.

Twenty-five years later my colleague Sharon G. Kujawa of Massachusetts Eye and Ear and I were trying to determine whether one episode of acoustic overstimulation in the ears of young mice could accelerate the onset of age-related hearing loss. The noise to which we exposed the animals was designed to produce only a temporary elevation of auditory thresholds and thus no permanent hair cell damage. As expected, the rodent cochleas looked normal a few days after exposure. But as we examined the animals from six months to two years later, we saw an accumulating loss of auditory nerve fibers, despite the presence of intact hair cells.

Fortunately, much had been learned since the 1980s about how to explore the molecular structure of these synapses. Antibodies had become available that could bind to, and tag with, different fluorescent markers, structures on each side of the synapse between the inner hair cell and auditory nerve fiber. The tags allowed us to count synapses easily under a light microscope. We quickly accumulated data showing that a few days after noise expo-

A FEW SIMPLE STEPS

How to Protect Your Hearing

In animal studies in several different species, we have produced irreversible nerve damage in the ear with two hours of continuous exposure to noise at 100 to 104 decibels (dB). There is every reason to believe that human ears are just as sensitive. Most daily exposures in our lives do not continue for that long. Nevertheless, it is prudent to avoid unprotected exposure to any sounds in excess of 100 dB.

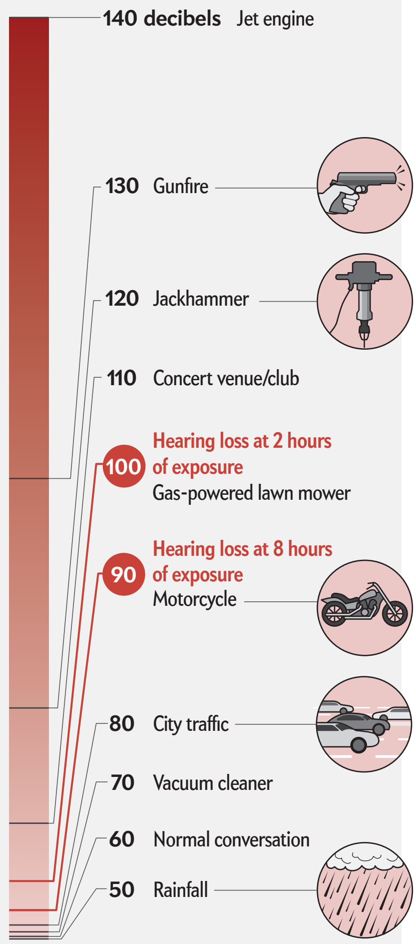
Many sounds in daily life take us into a danger zone. Concert venues and clubs routinely produce peak levels of 115 dB and average levels in excess of 105 dB. Gas-powered leaf blowers and lawn mowers reach levels at the users' ears between 95 and 105 dB, as do power tools such as circular saws. Frequency of the sounds matters. The more high-pitched whine of a belt sander is more dangerous at the same decibel level than the lower-pitched roar of an undermuffled motorcycle. Jackhammers produce levels of 120 dB even for passersby, and the rapid-fire impulses of the metal rod on concrete produce lots of the dangerous high-pitched sounds.

What can we do? These days almost all of us have access to surprisingly accurate sound-level meters in our pockets or purses. There are numerous free or inexpensive apps for iOS and Android phones that provide reliable readings of sound pressure produced by a musical instrument or a car backfiring to within 1 to 2 dB of the most expensive professional sound-monitoring equipment. The app for iOS that worked best for me, Sound Level Meter Pro, is still under $20 and gave me readings in my laboratory that were accurate to less than 0.1 dB.

Once you are aware of which sounds in your environment are potentially dangerous, the good news is that effective ear protection is cheap, easy to use and extremely portable. If properly inserted, the foam-type insert plugs can attenuate the sound level by 30 dB in the most dangerous frequency regions. Roll one between your fingers to squeeze it into the thinnest cylinder you can and then quickly insert it as deeply in your ear canal as you can. It is no more difficult or dangerous to do so than putting in earbud headphones. Let them slowly expand, and within a minute you are ready to rock and roll.

If you are attending a concert, these foam earplugs provide too much sound muffling. When you want to hear the sound but just at a lower (safe) level, use "musicians' ear plugs." Several brands are available online for $10 to $15 a pair. They are designed to provide 10 to 20 dB of sound attenuation, with equal muffling of low- and high-pitched sounds, so that the timbre of music is unaffected.

Most important, pay attention to what your ears are telling you. If you have left an event or an activity sensing that sounds seem muffled, like you have cotton in your ears, or if you have ringing in your ears, odds are that you have destroyed some auditory nerve synapses. Don't despair but try not to let it happen again. *—M.C.L.*



Graphic by Amanda Montañez

sure, when the auditory threshold had returned to normal, as many as half of the auditory nerve synapses were gone and never regenerated. The loss of the rest of the neurons—the cell bodies and the axons that project to the brain stem—became evident within a few months. By two years, half of the auditory neurons had completely disappeared. As soon as the synapses were destroyed, the affected fibers were of no use and did not respond to sounds of any intensity.

In the past few years we have documented noise-induced degeneration of synapses in mice, guinea pigs and chinchillas—and in postmortem human tissue. We have shown in the animal studies and in human ears that the loss of connections between auditory nerve fibers and hair cells occurs before the threshold elevations associated with hair cell loss. The idea that auditory nerve damage causes a kind of hidden hearing loss—an important component of noise-induced and age-related hearing impairment—has now become widely accepted, and many auditory scientists and clinicians are working to develop tests to determine if the problem is widespread and if our noisy lifestyles are leading to an epidemic of ear damage in people of all ages.

REPAIRING NERVES

PUT IN ITS SIMPLEST TERMS, the audiogram, the gold standard test of hearing, measures auditory thresholds and is a sensitive gauge of cochlear hair cell damage. Yet it is a very poor indicator of damage to auditory nerve fibers. Our research has shown that the nerve damage of hidden hearing loss does not affect the ability to detect the presence of sound, but it most likely degrades our ability to understand speech and other complex sounds. In fact, it may be a significant contributor to the classic complaint of the elderly: "I can hear people speaking but can't make out what they are saying."

Audiologists have long known that two people with similar audiograms can perform very differently on so-called speech-in-noise tests, which measure the number of words correctly identified as the level of a background noise increases. Previously they have ascribed these differences to brain processing. Our research suggests that much of it arises because of differences in the surviving population of auditory nerve fibers.

Hidden hearing loss may also help explain other common hearing-related complaints, including tinnitus (ringing in the ears) and hyperacusis (inability to tolerate even sounds of moderate loudness). These conditions often persist even when an audiogram flags no problem. In the past, scientists and clinicians have pointed to the normal audiogram of a tinnitus or hyperacusis sufferer and concluded, again, that the problem must arise in the brain. We suggest instead that the damage may have taken place in the auditory nerve.

Our research raises questions about the risks of routine exposure to loud music at concerts and clubs and via personal listening devices. Although noise-induced hearing loss is clearly a problem among professional musicians, even those playing classical music, epidemiological studies of casual listeners have consistently failed to find substantial impact on their audiograms. The federal guidelines developed to minimize noise damage in the U.S. workforce are all based on the presumption that if postexposure thresholds return to normal, the ear has fully recovered. As we have learned, this assumption is wrong; thus, it naturally follows that present noise regulations may be inadequate to prevent widespread noise-induced nerve damage and the hearing impairment that it causes.

To tackle this question, we need better diagnostic tests for auditory nerve damage, short of counting synapses in postmortem tissue. One promising approach is based on an existing measure of the electrical activity in auditory neurons, called the auditory brain stem response (ABR). The ABR can be measured in an awake or sleeping subject, fitted with scalp electrodes to measure electrical activity (electroencephalography) in response to the presentation of tone bursts of different frequencies and sound-pressure levels. Historically the ABR test has been interpreted largely on a pass-fail basis: the presence of a clear sound-evoked electrical response is interpreted as normal hearing, and the absence of a response is evidence of impairment.

In animal work, we have shown that the amplitude of the ABR at high sound levels is very informative: it grows in proportion to the number of auditory nerve fibers that retain a viable connection with inner hair cells. Correspondingly, a recent epidemiological study inspired by our research has used a variant of the ABR test on a group of British college students with normal audiograms and found smaller response amplitudes among those who report having been repeatedly exposed to the din of clubs and concerts.

In search of potential treatments for hidden hearing loss, we are now asking whether we can reverse the noise-induced degeneration by treating the surviving neurons with chemicals designed to regrow nerve fibers, reestablishing connections to inner hair cells. Although the synapses themselves are destroyed immediately after the noise exposure, the slowness of the degeneration of the rest of the nerve (its cell body and axons) makes us optimistic that normal function can be restored in many human subjects. We have had encouraging results in animal studies by delivering neurotrophins (nerve growth promoters) directly to the inner ear.

Hidden hearing loss may soon be treatable by injection through the eardrum of gels that slowly release neurotrophins to restore synapses months or years after a noise insult. They would be administered immediately after exposure to loud noise, such as the explosion at the finish line of the Boston Marathon in 2013 that damaged the hearing of more than 100 spectators. An otologist may one day be able to deliver drugs to the cochlea using a minimally invasive treatment for noise-induced ear damage as easily as an ophthalmologist corrects a myopic eye by laser surgery of the lens. SA

MORE TO EXPLORE

Adding Insult to Injury: Cochlear Nerve Degeneration after "Temporary" Noise-Induced Hearing Loss. Sharon G. Kujawa and M. Charles Liberman in *Journal of Neuroscience,* Vol. 29, No. 45, pages 14,077–14,085; November 11, 2009.

Synaptopathy in the Noise-Exposed and Aging Cochlea: Primary Neural Degeneration in Acquired Sensorineural Hearing Loss. Sharon G. Kujawa and M. Charles Liberman in *Hearing Research*. Published online March 11, 2015.

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Regaining Balance with Bionic Ears. Charles C. Della Santina; April 2010.

scientificamerican.com/magazine/sa

A NEW VISION FOR TESTING

Too often school assessments heighten anxiety and hinder learning. New research shows how to reverse the trend

By Annie Murphy Paul

IN BRIEF

Since the enactment of No Child Left Behind in 2002, parents' and teachers' opposition to the law's mandate to test "every child, every year" in grades three through eight has been intensifying.

Critics charge that the high-stakes assessments inflict anxiety on students and teachers, turning classrooms into test-preparation factories instead of laboratories of meaningful learning.

Research in cognitive science and psychology shows that testing, done right, can be an effective way to learn. Taking tests can produce better recall of facts and a deeper understanding than an education devoid of exams.

Tests being developed to assess how well students have met the Common Core State Standards show promise as evaluations of deep learning.

Illustrations by Mario Wagner

Annie Murphy Paul is a frequent contributor to the *New York Times*, *Time* magazine and Slate. Paul is author of *The Cult of Personality Testing* and *Origins*, which was included in the *New York Times'* list of 100 Notable Books of 2010. Her next book, forthcoming from Crown, is entitled *Brilliant: The Science of How We Get Smarter*.

Who was the first American to orbit Earth?

A NEIL ARMSTRONG
B YURI GAGARIN
C JOHN GLENN
D NIKITA KHRUSHCHEV

In schools across the U.S., multiple-choice questions such as this one provoke anxiety, even dread. Their appearance means it is testing time, and tests are big, important, excruciatingly unpleasant events.

But not at Columbia Middle School in Illinois, in the classroom of eighth grade history teacher Patrice Bain. Bain has lively blue eyes, a quick smile, and spiky platinum hair that looks punkish and pixieish at the same time. After displaying the question on a smartboard, she pauses as her students enter their responses on numbered devices known as clickers.

"Okay, has everyone put in their answers?" she asks. "Number 19, we're waiting on you!" Hurriedly, 19 punches in a selection, and together Bain and her students look over the class's responses, now displayed at the bottom of the smartboard screen. "Most of you got it—John Glenn—very nice." She chuckles and shakes her head at the answer three of her students have submitted. "Oh, my darlings," says Bain in playful reproach. "Khrushchev was *not* an astronaut!"

Bain moves on to the next question, briskly repeating the process of asking, answering and explaining as she and her students work through the decade of the 1960s.

The failed Bay of Pigs invasion involved the United States and which country?

A HONDURAS
B HAITI
C CUBA
D GUATEMALA

When every student gives the correct answer, the class members raise their hands and wiggle their fingers in unison, an exuberant gesture they call "spirit fingers." This is the case with the Bay of Pigs question: every student nails it.

"All right!" Bain enthuses. "That's our fifth spirit fingers today!"

The banter in Bain's classroom is a world away from the tense standoffs at public schools around the country. Since the enactment of No Child Left Behind in 2002, parents' and teachers' opposition to the law's mandate to test "every child, every year" in grades three through eight has been intensifying. A growing number of parents are withdrawing their children from the annual state tests; the epicenter of the "opt-out" movement may be New York State, where as many as 90 percent of students in some districts reportedly refused to take the year-end examination last spring. Critics of U.S. schools' heavy emphasis on testing charge that the high-stakes assessments inflict anxiety on students and teachers, turning classrooms into test-preparation factories instead of laboratories of genuine, meaningful learning.

In the always polarizing debate over how American students should be educated, testing has become the most controversial issue of all. Yet a crucial piece has been largely missing from the discussion so far. Research in cognitive science and psychology shows that testing, done right, can be an exceptionally effective way to learn. Taking tests, as well as engaging in well-designed activities before and after tests, can produce better recall of facts—and deeper and more complex understanding—than an education without exams. But a testing regime that actively supports learning, in addition to simply assessing, would look very different from the way American schools "do" testing today.

What Bain is doing in her classroom is called retrieval practice. The practice has a well-established base of empirical support in the academic literature, going back almost 100 years—but Bain, unaware of this research, worked out something very similar on her own over the course of a 21-year career in the classroom.

"I've been told I'm a wonderful teacher, which is nice to hear, but at the same time I feel the need to tell people: 'No, it's not me—it's the method,' " says Bain in an interview after her class has ended. "I felt my way into this approach, and I've seen it work such wonders that I want to get up on a mountaintop and shout so everyone can hear me: 'You should be doing this, too!' But it's been hard to persuade other teachers to try it."

Then, eight years ago, she met Mark McDaniel through a mutual acquaintance. McDaniel is a psychology professor at Washington University in St. Louis, a half an hour's drive from Bain's school. McDaniel had started to describe to Bain his research on retrieval practice when she broke in with an exclamation. "Patrice said, 'I do that in my classroom! It works!'" McDaniel recalls. He went on to explain to Bain that what he and his colleagues refer to as retrieval practice is, essentially, testing. "We used to call it 'the testing effect' until we got smart and realized that no teacher or parent would want to touch a technique that had the word 'test' in it," McDaniel notes now.

Retrieval practice does not use testing as a tool of assessment. Rather it treats tests as occasions for learning, which makes sense only once we recognize that we have misunderstood the nature of testing. We think of tests as a kind of dipstick that we insert into a student's head, an indicator that tells us how high the level of knowledge has risen in there—when in fact, every time a student calls up knowledge from memory, that memory *changes.* Its mental representation becomes stronger, more stable and more accessible.

Why would this be? It makes sense considering that we could not possibly remember everything we encounter, says Jeffrey Karpicke, a professor of cognitive psychology at Purdue University. Given that our memory is necessarily selective, the usefulness of a fact or idea—as demonstrated by how often we have had reason to recall it—makes a sound basis for selection. "Our minds are sensitive to the likelihood that we'll need knowledge at a future time, and if we retrieve a piece of information now, there's a good chance we'll need it again," Karpicke explains. "The process of retrieving a memory alters that memory in anticipation of demands we may encounter in the future."

Studies employing functional magnetic resonance imaging of the brain are beginning to reveal the neural mechanisms behind the testing effect. In the handful of studies that have been conducted so far, scientists have found that calling up information from memory, as compared with simply restudying it, produces higher levels of activity in particular areas of the brain. These brain regions are associated with the so-called consolidation, or stabilization, of memories and with the generation of cues that make memories readily accessible later on. Across several studies, researchers have demonstrated that the more active these regions are during an initial learning session, the more successful is study participants' recall weeks or months later.

According to Karpicke, retrieving is the principal way learning happens. "Recalling information we've already stored in memory is a more powerful learning event than storing that information in the first place," he says. "Retrieval is ultimately the process that makes new memories stick." Not only does retrieval practice help students remember the specific information they retrieved, it also improves retention for related information that was *not* directly tested. Researchers theorize that while sifting through our mind for the particular piece of information we are trying to recollect, we call up associated memories and in so doing strengthen them as well. Retrieval practice also helps to prevent students from confusing the material they are currently learning with material they learned previously and even appears to prepare students' minds to absorb the material still more thoroughly when they encounter it again after testing (a phenomenon researchers call "test-potentiated learning").

Hundreds of studies have demonstrated that retrieval practice is better at improving retention than just about any other method learners could use. To cite one example: in a study published in 2008 by Karpicke and his mentor, Henry Roediger III of Washington University, the authors reported that students who quizzed themselves on vocabulary terms remembered 80 percent of the words later on, whereas students who studied the words by repeatedly reading them over remembered only about a third of the words. Retrieval practice is especially powerful compared with students' most favored study strategies: highlighting and rereading their notes and textbooks, practices that a recent review found to be among the *least* effective.

And testing does not merely enhance the recall of isolated facts. The process of pulling up information from memory also fosters what researchers call deep learning. Students engaging in deep learning are able to draw inferences from, and make connections among, the facts they know and are able to apply their knowledge in varied contexts (a process learning scientists refer to as transfer). In an article published in 2011 in the journal *Science,* Karpicke and his Purdue colleague Janell Blunt explicitly compared retrieval practice with a study technique known as concept mapping. An activity favored by many teachers as a way to promote deep learning, concept mapping asks students to draw a diagram that depicts the body of knowledge they are learning, with the relations among concepts represented by links among nodes, like roads linking cities on a map.

In their study, Karpicke and Blunt directed groups of undergraduate volunteers—200 in all—to read a passage taken from a science textbook. One group was then asked to create a concept map while referring to the text; another group was asked to recall, from memory, as much information as they could from the text they had just read. On a test given to all the students a week later, the retrieval-practice group was better able to recall the concepts presented in the text than the concept-mapping group. More striking, the former group was also better able to draw inferences and make connections among multiple concepts contained in the text. Overall, Karpicke and Blunt concluded, retrieval practice was about 50 percent more effective at promoting both factual and deep learning.

Transfer—the ability to take knowledge learned in one context and apply it to another—is the ultimate goal of deep learning. In an article published in 2010 University of Texas at Austin psychologist Andrew Butler demonstrated that retrieval practice promotes transfer better than the conventional approach of studying by rereading. In Butler's experiment, students engaged either in rereading or in retrieval practice after reading a text that pertained to one "knowledge domain"—in this case, bats' use of sound waves to find their way around. A week later the students were asked to transfer what they had learned about bats to a second knowledge domain: the navigational use of sound waves by submarines. Students who had quizzed themselves on the original text about bats were better able to transfer their bat learning to submarines.

Robust though such findings are, they were until recently almost exclusively made in the laboratory, with college students as subjects. McDaniel had long wanted to apply retrieval practice in real-world schools, but gaining access to K–12 classrooms was a challenge. With Bain's help, McDaniel and two of his Washington University colleagues, Roediger and Kathleen McDermott,

TESTING THE TEAM PLAYER

The world's most watched test, the PISA, ventures into a new domain: instant messaging *By Peg Tyre*

When tens of thousands of 15-year-olds worldwide sit down at computers to take the Program for International Student Assessment (PISA) examination this fall, they will be tested on reading, math and science. They will also tackle a new and controversial series of questions designed to measure "collaborative problem solving skills." Instead of short-answer questions or lengthier explanations, the test taker will record outcomes of games, solve jigsaw puzzles and perform experiments with the help of a virtual partner that the test taker can communicate with by typing in a chat box. Although the new test domain is still experimental, PISA officials believe the results from these novel problems will push governments to better equip their young people to thrive in the global economy.

Critics of the unit say that PISA has stepped backward into an old and acrimonious debate about whether skills such as critical thinking and collaboration are teachable skills and whether they can be taught independent of content.

Given the pace of technological innovation, schools must adapt, and the new domain gives schools a road map to do that, says Jenny Bradshaw, senior PISA project manager, who oversees the test: "Working with unseen partners, especially online, will become a bedrock skill for career success. Increasingly, this is the way the workplace and the world will function."

It is a departure for the 15-year-old exam, which is coordinated by the Organization for Economic Co-operation and Development (OECD), a coalition of 34 member countries guided by industry. Since it was rolled out in 2000, the PISA exam has measured a student's ability to use reading, math and science in real-life settings. The PISA rankings and the headlines they generate quickly became a flashpoint for policy makers concerned about international competitiveness. The PISA score ranking has fueled, at least in part, a patchwork of efforts at school reform in the U.S. and Europe. America's mediocre performance on the PISA helped to prompt President Barack Obama to vow in 2009 that U.S. students must "move from the middle to the top of the pack in science and math" within a decade.

In 2008 tech industry giants Cisco, Intel and Microsoft, concerned that the job applicants they were seeing were poorly prepared for crucial tasks, began funding their own research through a group called Assessment & Teaching of 21st Century Skills (ATC21S) to identify and promote so-called 21st-century skills—roughly the ability to think critically and creatively, to work cooperatively, and to adapt to the evolving use of technology in business and society. Over several years ATC21S persuaded PISA to begin testing students across the globe for some of these abilities—and found academics to provide a research framework for how this might be done.

Three years ago the PISA exam added questions that were supposed to ferret out the problem-solving abilities of 15-year-olds around the globe. (PISA says Chinese students are good problem solvers. Israelis, not so much. Americans fall somewhere in the middle.) A wired, global economy, the test framers decided, requires an even more specific set of skills—group problem solving mediated by the Internet. This year PISA will have students in 51 countries put collaborative problem solving under the microscope.

The test questions themselves are alternately fun and frustrating. Although researchers at ATC21S believe it is best to test collabor-

set up a randomized controlled trial at Columbia Middle School that ultimately involved nine teachers and more than 1,400 students. During the course of the experiment, sixth, seventh and eighth graders learned about science and social studies in one of two ways: 1) material was presented once, then teachers reviewed it with students three times; 2) material was presented once, and students were quizzed on it three times (using clickers like the ones in Bain's current classroom).

When the results of students' regular unit tests were calculated, the difference between the two approaches was clear: students earned an average grade of C+ on material that had been reviewed and A– on material that had been quizzed. On a follow-up test administered eight months later, students still remembered the information they had been quizzed on much better than the information they had reviewed.

"I had always thought of tests as a way to assess—not as a way to learn—so initially I was skeptical," says Andria Matzenbacher, a former teacher at Columbia who now works as an instructional designer. "But I was blown away by the difference retrieval practice made in the students' performance." Bain, for one, was not surprised. "I knew that this method works, but it was good to see it proven scientifically," she says. McDaniel, Roediger and McDermott eventually extended the study to nearby Columbia High School, where quizzing generated similarly impressive results. In an effort to make retrieval practice a common strategy in classrooms across the country, the Washington University team (with the help of research associate Pooja K. Agarwal, now at Harvard University) developed a manual for teachers, *How to Use Retrieval Practice to Improve Learning*.

Even with the weight of evidence behind them, however, advocates of retrieval practice must still contend with a reflexively negative reaction to testing among many teachers and parents. They also encounter a more thoughtful objection, which goes something like this: American students are tested so much already—far more often than students in other countries, such as Finland and Singapore, which regularly place well ahead of the U.S. in international evaluations. If testing is such a great way to learn, why aren't our students doing better?

Marsha Lovett has a ready answer to that question. Lovett, director of the Eberly Center for Teaching Excellence and Educational Innovation at Carnegie Mellon University, is an expert on "metacognition"—the capacity to think about our own learning, to be aware of what we know and do not know, and to use that awareness to effectively manage the learning process.

Yes, Lovett says, American students take a lot of tests. It is what happens afterward—or more precisely, what *does not* hap-

ative problems through actual collaboration, PISA test takers will be paired with a virtual partner dubbed "Abby." Together the test taker and Abby will be expected, for example, to determine the prime conditions for fish living in an aquarium when the tester controls water, scenery and lighting and Abby controls food, fish population and temperature. To solve the task, the student must build consensus around how to solve the problem, respond to concerns, clear up misunderstandings, share information from trials and synthesize the results to come up with the correct answer.

Plenty of critics say the new domains are a blunder. "Is there an independent set of skills—in this case, collaborative problem solving—that is transferable across domains of knowledge?" asks Tom Loveless, an education researcher at the Brookings Institution. "Is problem solving between two biologists the same as problem solving between two historians? Or is it different? Progressive educators since John Dewey have insisted it is the same, but we just don't know that."

School systems that want to prepare students for the future should help them achieve mastery of complex math, science and literacy instead of putting resources into promoting nebulous concepts.

PISA's Bradshaw acknowledges that questions do remain about the innovative domains but that she and her team believe it is an experiment worth trying. While PISA researchers conduct validation studies and focus groups on collaborative problem solving, others are already working on PISA's next frontier. By 2018 she says her team will have come up with a valid way to measure "global competence."

Because it is true in education that what gets tested gets taught, ATC21S is preparing for the international hand-wringing from low-ranked countries by offering videos of classrooms where the researchers say teachers and students are getting it right. It has also rolled out a MOOC (massive open online course) to train teachers how to bring collaborative problem solving into their classrooms; 30,000 teachers have enrolled in the course, and a quarter of them have completed it.

Peg Tyre is a longtime education journalist and author of *The Good School* and the bestselling book *The Trouble with Boys.* She is also director of strategy for the Edwin Gould Foundation, which invests in organizations that send low-income students to and through college.

pen—that causes these tests to fail to function as learning opportunities. Students often receive little information about what they got right and what they got wrong. "That kind of item-by-item feedback is essential to learning, and we're throwing that learning opportunity away," she says. In addition, students are rarely prompted to reflect in a big-picture way on their preparation for, and performance on, the test. "Often students just glance at the grade and then stuff the test away somewhere and never look at it again," Lovett says. "Again, that's a really important learning opportunity that we're letting go to waste."

A few years ago Lovett came up with a way to get students to engage in reflection after a test. She calls it an "exam wrapper." When the instructor hands back a graded test to a student, along with it comes a piece of paper literally wrapped around the test itself. On this paper is a list of questions: a short exercise that students are expected to complete and hand in. The wrapper that Lovett designed for a math exam includes such questions as:

How much time did you spend reviewing with each of the following:

- Reading class notes? ______ MINUTES
- Reworking old homework problems? ______ MINUTES
- Working additional problems? ______ MINUTES
- Reading the book? ______ MINUTES

Now that you have looked over your exam, estimate the percentage of points you lost due to each of the following:

- ______ % FROM NOT UNDERSTANDING A CONCEPT
- ______ % FROM NOT BEING CAREFUL (*I.E., CARELESS MISTAKES*)
- ______ % FROM NOT BEING ABLE TO FORMULATE AN APPROACH TO A PROBLEM
- ______ % FROM OTHER REASONS (*PLEASE SPECIFY*)

Based on the estimates above, what will you do differently in preparing for the next test? For example, will you change your study habits or try to sharpen specific skills? Please be specific. Also, what can we do to help?

The idea, Lovett says, is to get students thinking about what they did not know or did not understand, why they failed to grasp this information and how they could prepare more effectively in advance of the next test. Lovett has been promoting the use of exam wrappers to the Carnegie Mellon faculty for several years now, and a number of professors, especially in the sciences, have incorporated the technique into their courses. They hand out exam wrappers with graded exams, collect the wrappers once they are completed, and—cleverest of all—they hand *back* the wrappers at the time when students are preparing for the next test.

Does this practice make a difference? In 2013 Lovett published a study of exam wrappers as a chapter in the edited volume *Using Reflection and Metacognition to Improve Student Learning*. It reported that the metacognitive skills of students in classes that used exam wrappers increased more across the semester than those of students in courses that did not employ exam wrappers. In addition, an end-of-semester survey found that among students who were given exam wrappers, more than half cited specific changes they had made in their approach to learning and studying as a result of filling out the wrapper.

The practice of using exam wrappers is beginning to spread to other universities and to K–12 schools. Lorie Xikes teaches at Riverdale High School in Fort Myers, Fla., and has used exam wrappers in her AP Biology class. When she hands back graded tests, the exam wrapper includes such questions as:

Based on your responses to the questions above, name at least three things you will do differently in preparing for the next test. BE SPECIFIC.

Approximately how much time did you spend preparing for the test? *(BE HONEST)*

Was the TV/radio/computer on? Were you on any social media site while studying? Were you playing video games? *(BE HONEST)*

Now that you have looked over the test, check the following areas that you had a hard time with:

- APPLYING DEFINITIONS ___________
- LACK OF UNDERSTANDING CONCEPTS ________
- CARELESS MISTAKES ___________
- READING A CHART OR GRAPH ___________

"Students usually just want to know their grade, and that's it," Xikes says. "Having them fill out the exam wrapper makes them stop and think about how they go about getting ready for a test and whether their approach is working for them or not."

In addition to distributing exam wrappers, Xikes also devotes class time to going over the graded exam, question by question—feedback that helps students develop the crucial capacity of "metacognitive monitoring," that is, keeping tabs on what they know and what they still need to learn. Research on retrieval practice shows that testing can identify specific gaps in students' knowledge, as well as puncture the general overconfidence to which students are susceptible—but only if prompt feedback is provided as a corrective.

There is yet another feature of standardized state tests that prevents them from being used more effectively for learning. The questions they ask are overwhelmingly of a superficial nature—which leads, almost inevitably, to superficial learning.

Over time, repeated exposure to this testing-feedback loop can motivate students to develop the ability to monitor their own mental processes. Affluent students who receive a top-notch education may acquire this skill as a matter of course, but this capacity is often lacking among low-income students who attend struggling schools—holding out the hopeful possibility that retrieval practice could actually begin to close achievement gaps between the advantaged and the underprivileged.

This is just what James Pennebaker and Samuel Gosling, professors at the University of Texas at Austin, found when they instituted daily quizzes in the large psychology course they teach together. The quizzes were given online, using software that informed students whether they had responded correctly to a question immediately after they submitted an answer. The grades earned by the 901 students in the course featuring daily quizzes were, on average, about half a letter grade higher than those earned by a comparison group of 935 of Pennebaker and Gosling's previous students, who had experienced a more traditionally designed course covering the same material.

Astonishingly, students who took the daily quizzes in their psychology class also performed better in their *other* courses, during the semester they were enrolled in Pennebaker and Gosling's class and in the semesters that followed—suggesting that the frequent tests accompanied by feedback worked to improve their general skills of self-regulation. Most exciting to the professors, the daily quizzes led to a 50 percent reduction in the achievement gap, as measured by grades, among students of different social classes. "Repeated testing is a powerful practice that directly enhances learning and thinking skills, and it can be especially helpful to students who start off with a weaker academic background," Gosling says.

Gosling and Pennebaker, who (along with U.T. graduate student Jason Ferrell) published their findings on the effects of daily quizzes in 2013 in the journal *PLOS ONE,* credited the "rapid, targeted, and structured feedback" that students received with boosting the effectiveness of repeated testing. And therein lies a dilemma for American public school students, who take an average of 10 *standardized* tests a year in grades three through eight,

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according to a recent study conducted by the Center for American Progress. Unlike the instructor-written tests given by the teachers and professors profiled here, standardized tests are usually sold to schools by commercial publishing companies. Scores on these tests often arrive weeks or even months after the test is taken. And to maintain the security of test items—and to use the items again on future tests—testing firms do not offer item-by-item feedback, only a rather uninformative numerical score.

There is yet another feature of standardized state tests that prevents them from being used more effectively as occasions for learning. The questions they ask are overwhelmingly of a superficial nature—which leads, almost inevitably, to superficial learning.

If the state tests currently in use in U.S. were themselves assessed on the difficulty and depth of the questions they ask, almost all of them would flunk. That is the conclusion reached by Kun Yuan and Vi-Nhuan Le, both then behavioral scientists at RAND Corporation, a nonprofit think tank. In a report published in 2012 Yuan and Le evaluated the mathematics and English language arts tests offered by 17 states, rating each question on the tests on the cognitive challenge it poses to the test taker. The researchers used a tool called Webb's Depth of Knowledge—created by Norman Webb, a senior scientist at the Wisconsin Center for Education Research—which identifies four levels of mental rigor, from DOK1 (simple recall), to DOK2 (application of skills and concepts), through DOK3 (reasoning and inference), and DOK4 (extended planning and investigation).

Most questions on the state tests Yuan and Le examined were at level DOK1 or DOK2. The authors used level DOK4 as their benchmark for questions that measure deeper learning, and by this standard the tests are failing utterly. Only 1 to 6 percent of students were assessed on deeper learning in reading through state tests, Yuan and Le report; 2 to 3 percent were assessed on deeper learning in writing; and *0* percent were assessed on deeper learning in mathematics. "What tests measure matters because what's on the tests tends to drive instruction," observes Linda Darling-Hammond, emeritus professor at the Stanford Graduate School of Education and a national authority on learning and assessment. That is especially true, she notes, when rewards and punishments are attached to the outcomes of the tests, as is the case under the No Child Left Behind law and states' own "accountability" measures.

According to Darling-Hammond, the provisions of No Child Left Behind effectively forced states to employ inexpensive, multiple-choice tests that could be scored by machine—and it is all but impossible, she contends, for such tests to measure deep learning. But *other* kinds of tests could do so. Darling-Hammond wrote, with her Stanford colleague Frank Adamson, the 2014 book *Beyond the Bubble Test,* which describes a very different vision of assessment: tests that pose open-ended questions (the answers to which are evaluated by teachers, not machines); that call on students to develop and defend an argument; and that ask test takers to conduct a scientific experiment or construct a research report.

In the 1990s Darling-Hammond points out, some American states had begun to administer such tests; that effort ended with the passage of No Child Left Behind. She acknowledges that the movement toward more sophisticated tests also stalled because of concerns about logistics and cost. Still, assessing students in this way is not a pie-in-the-sky fantasy: Other nations, such as England and Australia, are doing so already. "Their students are performing the work of real scientists and historians, while our students are filling in bubbles," Darling-Hammond says. "It's pitiful."

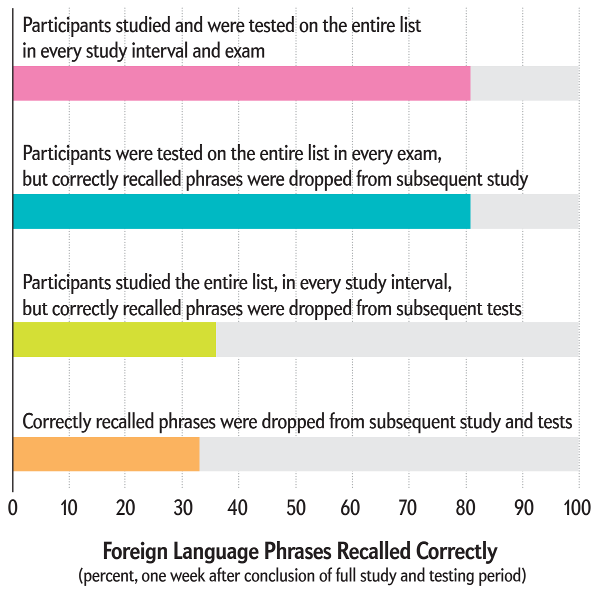
She does see some cause for optimism: A new generation of tests are being developed in the U.S. to assess how well students have met the Common Core State Standards, the set of academic benchmarks in literacy and math that have been adopted by 43 states. Two of these tests—Smarter Balanced and Partnership for Assessment of Readiness for College and Careers (PARCC)—show promise as tests of deep learning, says Darling-Hammond, pointing to a recent evaluation conducted by Joan Herman and Robert Linn, researchers at U.C.L.A.'s National Center for Research on Evaluation, Standards, and Student Testing (CRESST). Herman notes that both tests intend to emphasize questions at and above level 2 on Webb's Depth of Knowledge, with at least a third of a student's total possible score coming from questions at DOK3 and DOK4. "PARCC and Smarter Balanced may not go as far as we would have liked," Herman conceded in a blog post last year, but "they are likely to produce a big step forward."

RECALL

Tests That Teach

Quizzes can do more than assess learning—they can boost it. In a study designed to compare studying versus testing, published in 2008 in the journal *Science*, psychologists asked four groups of college students to learn 40 Swahili vocabulary words. The first group studied the words and was repeatedly tested on them. Other groups dropped the words they had memorized from subsequent study or testing, or both. One week later students who were repeatedly quizzed on all the words remembered 80 percent, whereas students who only studied the words remembered about a third.

Clear Benefits from Repeated Testing



SOURCE: "THE CRITICAL IMPORTANCE OF RETRIEVAL FOR LEARNING," BY JEFFREY D. KARPICKE AND HENRY L. ROEDIGER III, IN *SCIENCE*, VOL. 310; FEBRUARY 19, 2008

Graphic by Jen Christiansen

Michael Wysession is a professor of seismology at Washington University in St. Louis. He was the Earth and Space Sciences team leader for the National Research Council's report *A Framework for K–12 Science Education* and a member of the Writing Team for the Next Generation Science Standards. He has co-authored multiple K–12 textbooks with Pearson Prentice Hall.

KIDS ARE SCIENTISTS, TOO

Why the Next Generation Science Standards will succeed

By Michael Wysession

SUPPOSE YOU WANTED to teach children to play baseball or softball. How would you go about doing it? One approach might be to sit them down and start having them memorize the rules of the game, the dimensions of the field, the names and statistics of past players, and a host of other facts. You would stop teaching them periodically to review the material in preparation for multiple-choice assessment tests. The students who showed a great aptitude for memorizing large numbers of facts could go into honors classes where they would memorize even larger numbers of facts. At the end of the process, without ever leaving the classroom, how well do you think the children would be able to play baseball or softball? More important, how many would even want to?

Why have we thought that this process would work with teaching science to children?

The Next Generation Science Standards (NGSS) are intended to be a cure for this approach. They are the result of a bipartisan, states-led effort at rewriting K–12 science performance expectations in a way that will not only engage and excite students but also allow them to learn science by *doing* science, as opposed to memorizing facts *about* science. Research in science education has shown that letting students participate in the multiple practices that scientists actually do enables the children not only to enjoy and value the science more but to do a better job of retaining the scientific content. As the sports analogy suggests, this shouldn't be surprising—lots of kids know the rules of baseball and softball, and even statistics about their favorite players, but it isn't because they memorized them in a classroom.

The Next Generation Science Standards were completed in 2013, and so far about half of American students are committed to learning science aligned with these principles. At press time, 12 states and the District of Columbia have formally adopted them, several other states have settled on slight variations and many school districts in other states have also begun to adopt them.

It is tempting to suppose that things really won't change much: schools that used to teach to one set of standards will just be teaching to a new one. But that is not the case. The standards are an entirely new approach toward assessing student learning in science. There are no lists of facts that students will be required to memorize; the emphasis is on a higher level of understanding.

Here is an example of one performance expectation, taken from high school Earth and space science courses:

> *Students who demonstrate understanding can analyze geoscience data and the results from global climate models to make an evidence-based forecast of the current rate of global or regional climate change and associated future impacts to Earth systems.*

This example suggests several things about the next standards. First, aside from the content's being aimed at a higher level of understanding, action (in this case, analyzing and interpreting data) is the key here. Students are required to *do* something rather than to rely on memorization, categorization or classification. A typical assessment for this particular performance expectation might involve presenting students with a *new* data set and having them demonstrate their skills in constructing evidence-based forecasts and explanations.

Next, the standards contain substantial high school Earth and space science content—about a full year's worth; in contrast, most high schools today don't require any. According to a 2009 report by the National Center for Education Statistics of

the U.S. Department of Education, only a ninth of American students take advanced geoscience courses in high school, and most of those are environmental science courses. With the NGSS, there are 15 middle school Earth and space science performance expectations and 19 high school ones. This is in recognition not only of the legitimacy of the geosciences as a scientific field, on par with life and physical sciences, but of the relevance of the geosciences to modern human society. For both middle school and high school, science content would roughly consist of a year each of physical science (about a semester of both chemistry and physics), life science and geoscience. This is a departure from past curricula. As of 2013, only one state, North Carolina, required a year of high school geoscience (an environmental studies course), and only six states (Idaho, Kansas, Kentucky, Nebraska, New York and Utah) required the study of any high school Earth and space science concepts.

Third, climate science plays a significant role in the new standards. This is because of the dramatic global climate changes currently occurring on our planet, largely driven by human activities, and the recognition of the enormous influences that past climate changes have had on human history, including the migrations of peoples across continents and the rise and fall of civilizations.

The new standards face challenges. As we saw with the Common Core for math and English language arts, a project unrelated to the NGSS, any new way of teaching requires financial resources. We will need to develop educational materials (curricula, textbooks, assessments) and carry out research to assess them and improve their efficacy. We will need to provide professional development to current and future teachers to allow them to embrace the new emphasis on science and engineering practices and to align with shifts in science content. States and school districts will need to figure out how to best implement new curricula.

All of this needs to take place despite a political climate of distrust and cynicism toward some areas of science—such as, for example, the current attempts by the U.S. House of Representatives to micromanage the National Science Foundation and cut funding for the geosciences, especially climate science, at the same time that the U.S. Senate voted 98–1 that global warming is real.

Over the next few years, as the new standards are implemented state by state, children will be grabbing their gloves and heading out onto the field, so to speak, like the springtime start to the baseball and softball seasons. And once students see what science and engineering are *really* like, with the joys of discovery into how the universe operates, the camaraderie of teamwork, the sharing and debating of ideas, and the hands-on approach of designing and refining solutions to real problems with their own hands, there is a good chance they will stay more engaged and interested in science throughout their K–12 education and into adulthood. This increased engagement could lead to a stronger pipeline into STEM-related jobs, a better-informed voting citizenry and an enrichment of the personal lives of Americans. Perhaps science could even become the new national pastime? SA

MORE TO EXPLORE

The Critical Importance of Retrieval for Learning. Jeffrey D. Karpicke and Henry L. Roediger III in *Science,* Vol. 319, pages 966–968; February 15, 2008.

The Value of Applied Research: Retrieval Practice Improves Classroom Learning and Recommendations from a Teacher, a Principal, and a Scientist. Pooja K. Agarwal et al. in *Educational Psychology Review,* Vol. 24, No. 3, pages 437–448; September 2012.

Improving Students' Learning with Effective Learning Techniques: Promising Directions from Cognitive and Educational Psychology. John Dunlosky et al. in *Psychological Science in the Public Interest,* Vol. 14, No. 1, pages 4–58; January 2013.

Developing Assessments of Deeper Learning: The Costs and Benefits of Using Tests That Help Students Learn. Linda Darling-Hammond and Frank Adamson. Stanford Center for Opportunity Policy in Education, 2013.

FROM OUR ARCHIVES

Can the U.S. Get an "A" in Science? The Editors; Science Agenda, August 2012.

scientificamerican.com/magazine/sa

CLIMATE

CHANGE

In 1860 a naturalist named William Brewer set out to conduct the first geologic survey of the infant state of California. When Brewer arrived in the tiny adobe village of Los Angeles on December 2, he noted in his diary that "all that is wanted naturally to make it a paradise is water, more water." Three weeks later a raging torrent of water—the worst rainstorm in 11 years—destroyed many of the adobes. Such is weather in California.

The ancient record, etched in tree rings, shows patterns similar to those of today: long dry spells punctuated by fleeting wet years. In the year 1130, the rain tapered off and did not start again in earnest for another 40 years. Multidecade droughts show up in tree rings throughout California's history.

The simple lack of rain that shows up in tree rings, though, is no longer a practical definition of drought. A better one is more subjective: the difference between the moisture we have and the moisture we need. By that standard, this current drought is unprecedented. Yes, California is drier than at any time since 1895, when people began recording the weather. But it is also unnaturally hot—2014 was nearly two degrees Fahrenheit warm-

OF STATE

Searching for California's missing moisture *By Dan Baum*

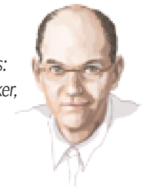
AFTER THREE YEARS of the worst drought in California's recorded history, Lake Oroville—photographed in July 2011 (*left*) and in August 2014 (*right*)—was down to 32 percent of capacity.

ALL PHOTOGRAPHS BY JUSTIN SULLIVAN *Getty Images*

er than the previous warmest year, and 2015 is shaping up to be even hotter—which cruelly boosts the land's need for water at just the moment when little is available. And human expectations for the land are unlike any in history. Almost 40 million people now call California home, and the rest of the country and much of the world depend on the food that grows there.

Californians can reel off the droughts they have endured: 1977, 1986–1991, 2001–2002, 2006–2007 and this one, which started in 2011. It is possible that future tree-ring scientists will see all of these not as a string of separate events but as the start of one of those medieval-style mega droughts; even those had wet years sprinkled within them. If the overcrowded salad bowl of California is indeed headed for decades of low precipitation in an era of unprecedented heat, the Golden State could end up being a very different place. In the worst case, it could be shorn of its lush agriculture and towering forests. In the best, its people could marshal the innovation for which they are famous and make their state the world's laboratory for water conservation and reuse. Either way, a painful adaptation to the new normal is under way.

Dan Baum is author, most recently, of *Gun Guys: A Road Trip*. A former staff writer for the *New Yorker*, he has reported from five continents.



To understand California's drought, you have to follow the water. This journey is full of surprises, starting with the fact that it begins some 6,000 miles away, out among the verdant western Pacific archipelagoes of Fiji, Vanuatu and the Solomon Islands.

Typically the sun warms the Pacific all along the equator, and the prevailing east-to-west surface winds push warm water into the island-rich sea west of the international date line. There the water literally piles up into a huge "mound" that is not only a few degrees warmer than the sea off the coast of South America but also about four feet higher. All of that heat fuels thunderstorms, which thrust moisture high into the atmosphere, where the jet stream—high-altitude winds that blow east instead of west—catches it for the trip to North America.

If the equatorial mound of hot water stays roughly west of the date line, we get La Niña, which is associated with droughts in the southwestern U.S. If the equatorial winds at the ocean's surface weaken or reverse and the mound slides east of the date line—and if the effect is sufficiently pronounced—we get El Niño, which brings additional rain to the West. What is happening now does not really resemble either El Niño or La Niña. That spot west of the date line during the past few winters was half a degree higher than the average 30 years ago, which is a lot in climate terms. It also got about a foot of extra rain in the winter of 2013–2014, as well as a Category 5 cyclone, which heaved a huge amount of heat from the unusually warm ocean high into the upper atmosphere. Two more gigantic cyclones in the region in early 2015 did likewise.

Scientists are loath to say exactly what causes what in a changing climate, but something about that warm-water mound in the western Pacific—perhaps combined with a shrinking differential between temperatures at the equator and the poles—seems to be jamming the meteorological gears. A "ridge" of high atmospheric pressure has parked itself over the eastern Pacific in the path of the moist jet stream, and like a boulder that has rolled into a creek, it is displacing the flow and pushing the jet stream north. What would have been California's water has been falling in enormous quantities onto Alaska and northwestern Canada, and it may have contributed to the historic snowfalls, from Chicago to Boston, this past winter and flooding in the U.K.

Such high-pressure jet stream–blocking ridges are common off the coast of California, but usually they dissipate within a few weeks, when storms break them apart. The current one has persisted since the winter of 2013–2014, diminishing only slightly from time to time and then, eerily, unusually, reassembling to ward off incoming moisture. Daniel Swain, a 25-year-old Ph.D. student at Stanford University, gave the anomaly the name that stuck: the Ridiculously Resilient Ridge, or Triple R. Several small storms punched through the Triple R this past winter—including a drenching rainstorm in February—but instead of dispersing, the ridge weirdly recoalesced. How long it will last, nobody can say.

Most of the water carried in from the western Pacific first touches ground high in the Sierra Nevada Mountains that run for 400 miles along the state's eastern border. I began searching for California's missing water there—specifically, at Echo Lake, high above Lake Tahoe. In wet years, the water blows in on the jet stream and falls here in titanic quantities. A man I know once skied into the area to find his cabin on the lakeshore, dug holes in the snow all over the side of the mountain to look for the house and never found it; he had to ski out in the dark. At Echo Lake this year, in contrast, almost no snow fell. In the lee of the Triple R, the winter of 2013–2014 saw historically low levels of Sierra Nevada snowpack, and this past winter was even worse—at only 5 percent of the average. In April the drifts at Echo Lake are usually human-high, but when I arrived on Tax Day, only a few tiny scraps of white huddled underneath the trees.

From Echo Lake, I drove 200 miles south, passing Yosemite National Park, to visit Nathan Stephenson, a plant ecologist for the U.S. Geological Survey who works among California's marquee giant trees in Sequoia National Park. Sequoia looms above the Central Valley's Tulare County, ground zero of the drought. The Kaweah River flows out of the park, down to the much depleted Lake Kaweah and then on down to the valley. Stephenson has seen droughts come and go in his 35 years in the park but never like this one. "I'd estimate from eyeballing that a third of the oaks on the slopes are dead or dying," he said, scanning a mountainside forest that, even to the untrained eye, looked pale and tired, dotted with brown trees. Stephenson is tall and lanky, with a gray beard and the sunny disposition of a man who gets paid to hang out in a national park. But he was morose as he gazed at the hillside from under the bill of his USGS hat. "This is only *April*," he marveled.

We climbed back into his Subaru and drove up the mountain to a copse of incense cedars riddled with specimens starkly golden-brown. "They're hundreds of years old and very resilient—hosts to few insects," Stephenson said. "We've jokingly called them 'the immortals' because they never seem to die." He paused and put a hand out to feel a cedar's brown needles. "I guess they're mortal now." Finally, we ascended to the kingdom

IN BRIEF

California's drought is unprecedented. Tree-ring records show that decades-long dry spells have hit the state before, but never when so many people were placing so many demands on the land.

The state is changing as a result. In the Sierra Nevada, the forests are shifting; old, big trees are dying and being replaced by smaller ones. Even the iconic sequoias could be at risk.

The Central Valley aquifer is literally collapsing, the result of unregulated groundwater pumping. Farmers are leaving fields fallow, crop trees are going up in flames and taps are running dry.

The state could become like Arizona. But there is hope. Creative thinking has begun, and plenty see the drought as an opportunity to rescue California and make money in the process.

FARMERS in the Central Valley town of Firebaugh walked their fields (*upper left*); nearby, almond trees withered (*upper right*), and signs protested cuts in water allocated to farmers (*lower right*). In Porterville, hundreds of homes were without water (*lower left*).

of the eponymous sequoias themselves, many of which stood amid heaps of their own dead needles—testimony to the way the drought was nibbling at their extremities.

The USGS has been tracking 20,000 trees of various types in 30 widely spaced plots here for as long as 33 years. The trees in them, sequoias included, are dying in ways both predictable and otherwise. In normal times, an unbroken thread of water extends from a tree's roots to every leaf or needle, siphoned up through tiny capillaries as the tree transpires water into the air. Now, though, trees of all types are dying of cavitation: the thread of water breaks, air bubbles get into the capillaries and that is that. Other trees slam shut the pores on their leaves during dry periods to retain water. But then they cannot breathe carbon dioxide. Usually moisture returns and the pores reopen before the trees asphyxiate, but this drought has been so long, dry and hot that many trees are fatally squeezed between holding onto their water and breathing. And then there are the beetles, attracted to drought-stressed trees, that are devastating enormous stands of pine throughout the West. Once a tree dies, the beetles fly off to the next. Sometimes, during this drought, they fly in swarms so intense that you can scoop them out of the air with a baseball cap. This past spring an aerial survey of a huge swath of California's Sierra Nevada forests, including Sequoia park, found more than 10 million dead trees—10 percent of the trees in the surveyed area, most of them killed in the previous year. If the drought continues long enough, it could sear the majestic forests off of California's high ground and annihilate the giant sequoias that include the General Sherman tree, at 275 feet in height and 37 feet across at the base, the biggest in the world, by volume.

A massive die-off would be an enormous loss for the state, but it could be dire for the planet, not only because it would release untold tons of carbon dioxide into an already warming atmosphere. Last year Stephenson was lead author of a massive study—of 673,046 trees of 403 species across six continents—which shocked the botanical community by finding that, contrary to popular belief, trees grow faster the bigger and older they get. If the Sierra Nevada forest continues its die-off, it will be repopulated by a very young forest, which might suck less climate-warming carbon dioxide from the atmosphere than the current, multiage one.

In wet years, the snow that piles up in the Sierra Nevada contains enough water to fill the state's reservoirs. Down the western slope it trickles each spring and summer, and left to its own devices, it finds its way into the next stop on our pursuit of California's absentee water—a gigantic feature of this crowded state that hides in plain sight: the 1,100-square-mile Sacramento–San Joaquin River Delta.

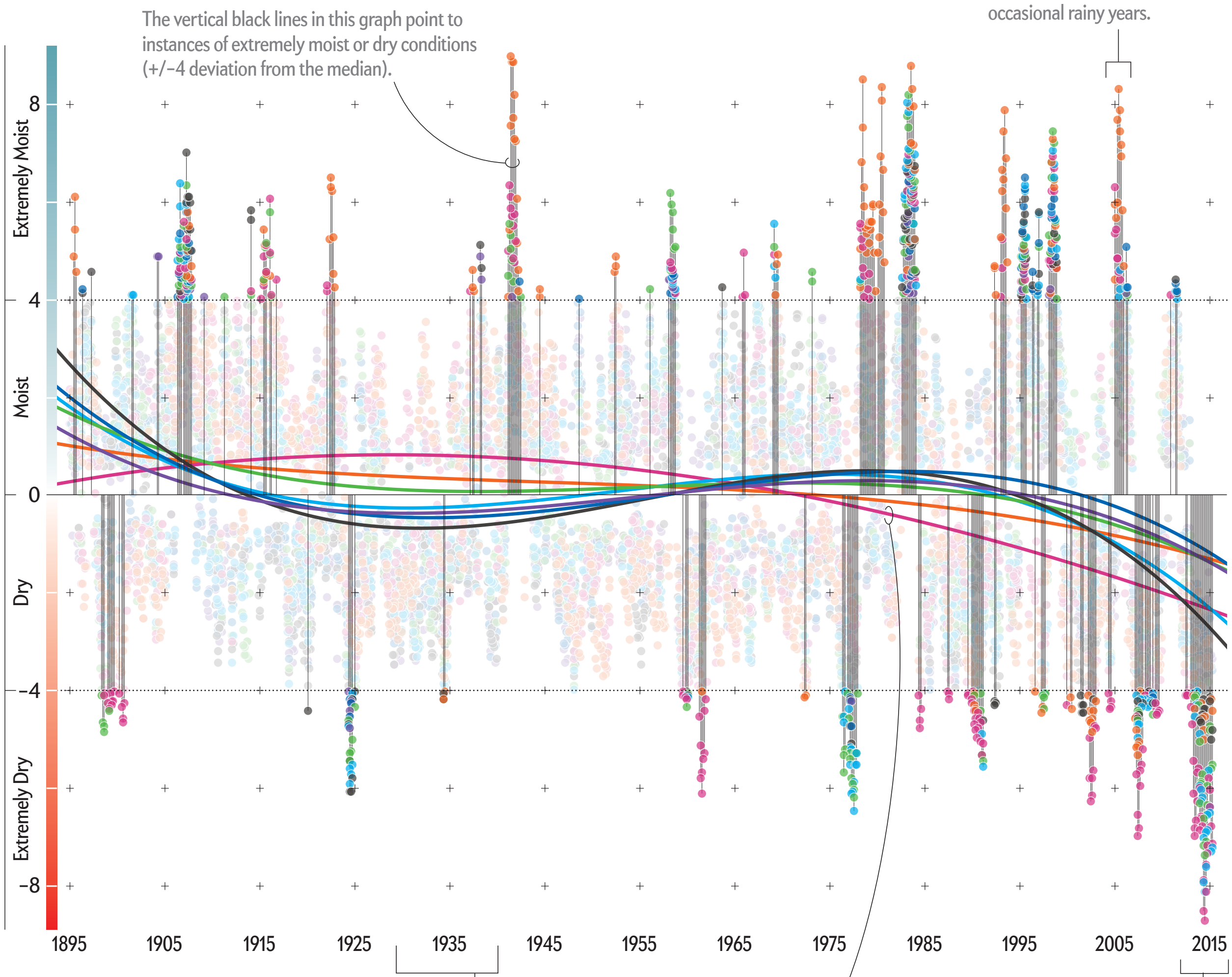
The delta lies just east of San Francisco Bay. Before the arrival of settlers, it was a freshwater marsh of channels and sloughs and islands, but it is now mostly planted in crops and even hosts

An Unprecedented Drought

By any measure, the current drought in California is historic. The chart below is based on the Palmer Hydrological Drought Index, a soil-moisture algorithm designed to measure the long-term impact of drought by taking into account reservoir levels, groundwater data and other slow-moving indicators. The data make clear that although extreme conditions—both wet and dry—have become more frequent since the 1970s, all regions of California have experienced an overall drying trend in recent decades.

Wet Spell

Recent dry years have been punctuated by unusually rainy years, but that moisture has not offset the overall drying trend. Similar patterns occurred centuries ago; the decades-long medieval megadroughts that appear in California tree-ring records also included occasional rainy years.



Palmer Hydrological Drought Index

Each dot on the graph above represents one month's Palmer Hydrological Drought Index value for each of seven regional divisions. Dots within the "normal" range (+4 to –4) are faded into the background.

- North Coast Drainage
- Sacramento Drainage
- Northeast Interior Basins
- Central Coast Drainage
- San Joaquin Drainage
- South Coast Drainage
- Southeast Desert Basins

The Dust Bowl Years

California was largely spared the ill effects of the Dust Bowl, which is why displaced farmers from the Great Plains fled there in search of work.

Trending Dry

The solid curves are polynomial trend lines tracing overall fluctuations in the conditions in California's seven regional divisions. The increasing density of vertical gray lines after 1975 indicate an increase in the frequency of both extreme conditions—both wet and dry. Overall, however, every trend line bends downward during this period, indicating that every region in the state is trending dry.

Widespread and Long-Lived Drought

One unusual and unpleasant feature of the current drought is that so many different regions in this large and geographically varied state are experiencing it at an extreme level.

SOURCE: NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION'S NATIONAL CENTERS FOR ENVIRONMENTAL INFORMATION

Graphic by Pitch Interactive

more than half a million people in such cities as Antioch and Rio Vista. But huge tracts remain undeveloped floodplain—spooky, jungly, dead-flat wilderness that the madding crowd hardly ever sees—shot through with about 700 miles of tangled waterways. This is the biggest estuary on the West Coast, the confluence of the rivers that drain the vast Sacramento and San Joaquin valleys, and it is the grand clearinghouse for California's managed surface water. Water released from northern reservoirs to southern farms and cities must pass through here. It took hours of crisscrossing dirt roads and causeways to find the little corner of the delta known as the Clifton Court Forebay, where loom the pump houses that push water down the wide, concrete-lined trench that is the California Aqueduct toward Los Angeles, 340 miles away, and through the Delta-Mendota Canal to the sprawling farms of the Central Valley.

California's surface water is so heavily managed that it seems more an industrial product than a natural resource. A network of state and federal reservoirs; a complex grid of canals and aqueducts; and a dizzying tangle of water laws, water rights, environmental regulations, court orders and legal opinions divide water up in ways guaranteed to infuriate everybody. About half the surface water is left in the streams, rivers and delta to maintain wetlands and fish habitat, to comply with the Endangered Species Act, and to keep saltwater from backing up through the delta and flowing into the canals and aqueduct.

The remaining half of California's surface water is allocated to humans: 20 percent to the cities—which in April were ordered by Governor Jerry Brown to reduce consumption by, on average, a quarter—and 80 percent to farmers. In theory. This year and last, surface water has been in such short supply that most farmers were allocated zero.

Given the micromanagement of California's surface water, it is shocking that the taking of groundwater, by far the majority of the state's water, is almost completely unregulated. California is the only state where you can pump as much groundwater as you like as long as you do not waste or sell it. The current drought has set off a kind of arms race in the Central Valley, with every farmer eager to go deeper than his or her neighbor, "like a bunch of four-year-olds with one milk shake and lots of straws," in the words of one agricultural economist. Nobody knows how much is being pumped out, but groundwater levels are historically low. The farmer with the deepest well in a given area draws down the water, and if that means the neighbors' wells go dry, so be it.

Some are going as deep as 1,500 feet to reach water that may have rained 10,000 years ago. Such "fossil" water, in contact with geologic substrata for that long, is frequently foul with arsenic, chromium, salt and other contaminants. Drilling that deep is also expensive. Farmers who can find a driller to do the job—waiting lists are a year long—might spend half a million dollars on the project, and that does not include the high cost of pumping the water to the surface from such abysmal depths.

About 190 miles south of the delta one afternoon, near the farm town of Visalia, I followed a plume of smoke to a field full of dead orange trees that had been bulldozed into piles the size of large houses and set alight. The owner, who stood watching gloomily, told me he had leased the 80 acres and its 10,600 healthy trees to a tenant farmer, who last spring had hooked up illegal pipes and sold the farm's well water to a neighbor, letting the trees die.

It is not just landowners who are getting hurt. Yolanda Serrato in East Porterville, Calif., a poor, unincorporated farmworker town in Tulare County, was watering her small lawn last December when the hose sputtered and the water stopped—for good. The shallow wells of about 400 of her neighbors went dry around the same time, leaving them dependent on a hodgepodge of public assistance and charity. When I met Serrato, she was leaning on her chain-link fence and peering down the street for the pickup truck that she hoped would bring her a few bottles of water. It was hard not to see East Porterville as a harbinger of a day when Californians are forced from their homes by a lack of water.

The first law of hydrodynamics is that water flows toward money. It is likely to be a long time before most Californians, especially in the coastal cities, confront dry taps. San Francisco draws its water from the pristine Hetch Hetchy Reservoir, 167 miles away in Yosemite. Los Angeles—as anybody who has seen the movie *Chinatown* knows—dried out the Owens Valley, more than 200 miles away, in the 1920s and now gets most of its water from reservoirs even farther north. As long as California has even a drop of water, it will doubtless run toward wealthy coastal residents.

In the Central Valley, however, the trouble is only beginning. To understand why, we have to follow California's water deep underground. The Central Valley is essentially a 20,000-square-mile trough of layered clay, gravel, silt and sand, wedged between mountain ranges of hard rock. Water travels laterally in layers of gravel and sand with ease, which is why a farmer pumping groundwater can suck water away from a neighbor. Moisture is primarily stored, though, in layers of clay, which drip their load slowly into the gravel and sand. It is the way in which clay stores water that makes the current pumping frenzy so worrisome.

Disasters have a way of catapulting scientists from obscurity to fame overnight. Michelle Sneed, a young USGS geologist, toiled for years to become an expert in a dull field—ground subsidence—that has suddenly become crucial to the state's future. With startlingly direct blue eyes and long, wavy hair, she seemed to be enjoying her moment as a scientific rock star. As we sat in her office in Sacramento, at the northeastern edge of the delta, she turned her palms up, intertwined her fingers and explained that the microscopic structure of clay consists of tiny plates cocked haphazardly. "Imagine how much water you could fit into your kitchen sink if you threw in a bunch of dinner plates and left them leaning on each other every which way," she said. Then she pivoted her hands to press the palms together. "Now imagine stacking those plates neatly and what that would do to the space for water between them." That is essentially what happens when too much water is pumped out of the ground too quickly; the microscopic plates in the clay slide into a stacked-up position. The clay layer, in other words, collapses.

Hundreds of feet above, the ground collapses with it. Vast areas of the Central Valley have subsided, since the 1920s, by nearly 30 feet. In just two years—between 2008 and 2010—more than a tenth of the Central Valley sank two inches. That makes work for road crews who fix cracked highways and bridges and for railroad workers who relevel track. It also complicates the delivery of water around the state. Canals and aqueducts can run for hundreds of miles without pumps because they slope ever so slightly downhill. It does not take much subsidence to interfere with the flow, which is what happened last year, among other places, at the spot where a big canal meets the San Luis Reservoir in central California. But the interruptions to water delivery are hardly the worst of it. Once subterranean clay collapses, it can never again store water. So California's pump-frenzied farmers are not only depleting the aquifer on which they depend, they are also destroying it.

The only hope is to recharge what is left of the aquifer as fast as possible. The problem is that not all ground is equally rechargeable. Underneath about half the Central Valley is Corcoran clay, the remains of an ancient lake bed, which can be punctured by wells but which, unlike most clay, remains largely impermeable to water. Geologists can identify areas with no Corcoran clay—areas that are permeable and thus geologically suitable to flood for groundwater recharge. But some are covered with subdivisions, shopping centers or farms; identifying permeable ground and getting permission to flood it is a formidable task.

IN PORTERVILLE, residents whose taps had gone dry filled buckets with nonpotable water in front of the Doyle County Fire Station.

Scientists at the University of California, Davis, are running an experiment with the Almond Board of California to see if almond orchards that sit above geologically appropriate soil can be flooded, when the trees are dormant in winter, to recharge the aquifer. That raises not only geologic questions but also legal ones: California law requires farmers to use the water that they receive from the state for "beneficial uses" only, and recharging groundwater might legally be banned as "overwatering." Then there is the question of whether a farmer who banks water this way has a claim to receive an equal amount later. And to flood a field or grove to recharge groundwater, it takes more than permission and legal rights; it takes water. Lately there is not enough water to nourish today's crops, let alone enough to bank for future ones. Any massive recharge scheme will have to wait for a wet year.

The crisis has been severe enough to give Governor Brown and the legislature cover to change California's 150-year-old water laws in a baby step toward regulating groundwater. Under a law passed last November, local water agencies in each of the state's 515 distinct groundwater basins will have five years to come up with plans for sustainable use and 25 more to achieve them. That is going to shake up the state politically because city water departments, farmer-run irrigation districts, county water commissions and other water-management agencies—all of which live in their own worlds, with their own proprietary data and competing interests—are going to have join into groundwater sustainability agencies, or GSAs, to share their most valuable resource. In a cheaply paneled temporary office building that serves as the office of the city of Tulare Water District, halfway down the San Joaquin Valley, I met a young man named Benjamin Siegel who has been assigned the thankless task creating a GSA with the city of Visalia and a local irrigation district. "It's like writing a new language," he said.

Fifteen miles up the road Denise Atkins, the county's administrative analyst for water resources, told me that just getting everybody to agree on who will have a voice in the local GSA is a nightmare, let alone getting people to agree to share data. "Five years ago if you wanted to ask a grower, 'How do you feel about a meter on your well?' you'd better wear Kevlar," she said. "Now farmers are getting enthusiastic about knowing how much water they use." She leaned across her cluttered desk, rolled her eyes and added, sotto voce, "Though it's usually, 'My neighbor is pumping too much.'"

Scientists differ on the explosive question of whether the drought is caused by anthropogenic climate change. The National Oceanic and Atmospheric Administration said no last year, the Intergovernmental Panel on Climate Change said maybe and a team of Stanford climate scientists that included Swain—christener of the Triple R—said yes. The Stanford crew modeled current and preindustrial climates and determined that the conditions associated with the Triple R are three times as likely now. But whether or not climate change is causing the drought, everybody seems to agree that the additional heat is exacerbating the effects of low moisture, from the forests of the Sierra Nevada to the farms of the Central Valley.

After years of something that looked kind of like La Niña, in March, NOAA declared the start of a weak El Niño but cautioned that it probably will not affect weather much in California anytime soon. California might have some wet years in its near future, but the soil from the top of the Sierra Nevada to the bottom of the Central Valley is so desiccated that it will take years to properly hydrate the ground and much longer to begin recharging the groundwater. The state can choose to view current conditions as an anomaly and "manage this as a disaster," but that would be a terrible mistake, said Noah Diffenbaugh, a senior fellow at the Woods Institute for the Environment at Stanford. "It's clear that California is in a different climate now."

If that different climate involves, say, a 30-year drought akin to the ones in the Middle Ages, the mountain forests will die off because their water is not managed, and the next casualty will be the farms and orchards of the Central Valley that have been so emblematic of California for the past century.

One line of thought about the end of California's agriculture

SCIENTIFIC AMERICAN ONLINE For a collection of stories on climate change and drought, go to ScientificAmerican.com/aug2015/drought

goes like this: So what? Agriculture constitutes only about 2 percent of California's economy, and the flood of inexpensive, water-intensive food that the world has enjoyed was perhaps always the unrealistic illusion of people without a millennium-long perspective. "*California* would be fine" without agriculture, Richard Howitt, a dry-witted, British-born agricultural economist at U.C. Davis, told me. "We'd turn into an Arizona economy. We'd phase out irrigated ag and move to movies [2.1 percent of California's gross domestic product], information technology [8 percent] and everything else." Fruit, nuts and vegetables would doubtless become more expensive for everybody, but California itself could easily survive on the manufacturing, health care, finance and education that make its economy the seventh largest in the world—especially if it was not diverting four fifths of its usable water to irrigated agriculture.

Realistically, though, it is hard to imagine a state as innovative as California simply allowing the pride of its fields to disappear. More than a third of the Central Valley's agriculture is in grapes and tree crops—almonds, walnuts, pistachios, citrus—that represent an enormous investment than can take as long as seven years after planting to pay off. Farmers are already turning to a vigorous high-tech industry that makes GPS-equipped irrigators, weather-based irrigation, soil-moisture sensors and other agroelectronics designed to reduce water use. Even more radically, in June the state took the unthinkable step of placing water restrictions on California's agricultural royalty—those who hold Gold Rush–era riparian water rights in the Sacramento and San Joaquin valleys that have long been considered inviolate. It is easy to get the sense, traveling around California, that the pain—but also the creative thinking—has only begun.

The drought is transforming California in almost every conceivable way— meteorologically, geologically, biologically, agriculturally, socially, economically and politically.

The drought is transforming California in almost every conceivable way—meteorologically, geologically, biologically, agriculturally, socially, economically and politically. The combination of low moisture and high temperature most likely will be the condition of the future. Even when sporadic wet years occur, the inexorably warming climate assures that precipitation will fall not as heavy snowpack that parcels out water slowly but as crashing torrents of rain. That is why last November Californians voted for Proposition 1—more than $7 billion for water infrastructure, almost half of which will go to building new dams and reservoirs—a public works project of massive proportions. And therein lies the silver lining in the California drought: one person's cost is another's opportunity.

The Army Corps of Engineers wants to pull the concrete out of an 11-mile stretch of the Los Angeles River—now an ugly storm drain that does little but funnel as much as 207 million gallons of water a day into the ocean. The project would allow at least some of that water to recharge the aquifer and inject more than $1 billion into the local economy.

Desalination has the potential to provide the coasts with nearly limitless water, but it is wildly expensive, has an enormous carbon footprint because it takes so much energy and generates oceans of intensely salty brine that are hard to dispose of safely. The real potential for drought management is in water conservation and recycling. The Pacific Institute, an environmental think tank in Oakland, estimates that just getting homeowners to use water more efficiently indoors and out could save California about three million acre-feet a year—close to a third of its urban water use.

Proposition 1 includes $725 million for water recycling—seven times more than the state has ever devoted to it. That is only about a fifth of what the Californian branch of the WateReuse Association, the trade group for the water-recycling industry, thinks it would take to maximize the potential for recycling in the state, but the state money is intended to attract city, county and private money to water reuse projects. Retrofitting city parks, golf courses, factories, office buildings and even homes with "purple pipe"—which carries water clean enough for landscaping, toilets and other nonpotable uses—is about to become a multimillion-dollar sector of the economy.

The transition has already started in Orange County, which since 2008 has been treating more than a third of its wastewater to potable standards and injecting it into the aquifer. The county makes another 17 percent of its wastewater clean enough for industrial processes, landscaping and such domestic uses as flushing toilets. The infrastructure was expensive, but most of the treated water costs the county a little more than half of what it would cost to import water from the rapidly depleting Colorado River. Last November, San Diego's city council voted to spend almost $3 billion on the equipment that will allow the city to recycle enough water for a third of its citizens. WateReuse insists that purifying wastewater could supply all the municipal needs of eight million people—a fifth of California's population—and create untold jobs in the bargain.

The new normal is a little frightening, but this is California. Problems, yes, but there's gold in them thar solutions. SA

MORE TO EXPLORE

Explaining Extreme Events of 2013 from a Climate Perspective. Edited by Stephanie C. Herring et al. in *Bulletin of the American Meteorological Society,* Vol. 95, No. 9, pages S1–S104; September 2014.

Unprecedented 21st Century Drought Risk in the American Southwest and Central Plains. Benjamin I. Cook, Toby R. Ault and Jason E. Smerdon in *Science Advances,* Vol. 1, No. 1, Article No. e1400082; February 1, 2015.

Climate Change and California Drought in the 21st Century. Michael E. Mann and Peter H. Gleick in *Proceedings of the National Academy of Sciences USA,* Vol. 112, No. 13, pages 3858–3859; March 31, 2015.

FROM OUR ARCHIVES

El Niño. Colin S. Ramage; June 1986.

The Jet Stream Is Getting Weird. Jeff Masters; December 2014.

scientificamerican.com/magazine/sa

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THOUGHT EXPERIMENT

Planet Hard Drive

What is the information storage capacity of Earth, and how full is it today? The answer tells us surprising things about the growth of order in the universe

By César A. Hidalgo

IN BRIEF

If we define information as order and then calculate the amount of information that our planet can hold, we find that Earth's hard drive is largely empty—despite billions of years of life and thousands of years of human cultural activity.

This thought experiment tells us interesting things about the emergence of order in the universe. Although the universe is hostile toward order—overall, entropy always tends to increase—information grows over time.

Humans are partly responsible for the growth of information on Earth, but we remain severely limited in our capacity to create order.

Illustration by Greg Mably

IN 2002 SETH LLOYD, A PROFESSOR OF QUANTUM COMPUTING AT THE MASSACHUSETTS INSTITUTE OF Technology, published a formula estimating the number of bits that could fit in the universe. A "bit" is a fundamental unit of information that represents the answer to a yes or no question. A computer stores bits in a transistor, but a bit can also be encoded in the state of a physical particle, such as the spin of an electron. Lloyd's formula exploited the physicality of information to estimate the rate at which physical systems can process and record information as a function of Planck's constant (an unimaginably tiny unit that is fundamental to quantum mechanics), the speed of light and the age of the universe. Lloyd concluded that our universe could fit a whopping 10^{90} bits, or a trillion trillion trillion trillion trillion trillion trillion megabits.

Lloyd developed his formula because his work on quantum computers, which use single atoms to encode information and perform computations, had him thinking about the universe in terms of bits that live in atoms. He performed a thought experiment, asking himself: What is the largest computer that could ever be built? The answer: one that would employ every atom in the universe. That computer could store 10^{90} bits.

But the beauty of Lloyd's formula is that it can be used to estimate the information-storing capacity of any physical system, not just the universe. Recently I have drawn inspiration from Lloyd's formula while exploring the computational capacities of economies and societies. Lloyd's formula does not incorporate much of the social and economic complexity inherent in our economies, but it gives us rough estimates of the capacity of systems to store and process information. Think of Earth as a hard drive. According to Lloyd's formula, the planet can store up to 10^{56} bits—roughly a trillion trillion trillion trillion gigabits. But is this planetary hard drive mostly empty or mostly full?

To answer that question, let us consider the work of Martin Hilbert and Priscilla López. In 2011 Hilbert and López, then at the University of Southern California and the Open University of Catalonia in Spain, respectively, published an estimate of the cultural information stored in our planet's texts, pictures and videos. They concluded that as of 2007, humans had stored 2×10^{21} bits, or two trillion gigabits. But there is much more information in our planet than what is contained in cultural artifacts. Information is also embodied in human-designed objects, such as your car and your shoes, and in biological systems, such as your ribosomes, mitochondria and DNA. Indeed, it turns out that most of the information contained in Earth is stored in the form of biomass. Based on Lloyd's formula, I estimate that Earth contains roughly 10^{44} bits. That figure might sound like a lot, but it is only a small fraction of the globe's capacity. If humans continued to generate 10^{21} bits every year, it would still take much more than a trillion ages of the universe to fill our planetary hard drive.

What these calculations tell us is that although Earth has an enormous capacity to store information, order is still rare. That insight, in turn, tells us a lot about how information is created and processed by the planet and the hurdles that could limit its growth in the future.

OUR COMPUTATIONAL UNIVERSE

THE FIRST THING the informational emptiness of our planet reveals is that information is hard to grow—difficult to make, tough to preserve and challenging to combine into new configurations. That deduction fits well with past observations and is explained by the universe's hostility toward the emergence of order. The second law of thermodynamics dictates that our universe has a natural tendency to average out, making order disappear. Heat flows from hot to cold, music vanishes as it travels through the air and the swirls in your latte quickly diffuse into milky clouds. This move from order to disorder is known as the growth of entropy.

Yet there are loopholes that allow pockets of order to emerge. Think of a biological cell, the human body or the man-made economy. These highly organized systems defy the increase of physical entropy that governs the universe as a whole, albeit locally. Information-rich systems can exist only as long as they "sweat" entropy at their seams, paying for their high levels of organization by expunging heat. "Entropy is the price of structure," as Nobel Prize–winning chemist Ilya Prigogine once cleverly noted.

Order emerges or persists in our universe thanks to three tricks. The first, and perhaps most familiar, trick involves the flow of energy. Imagine a bathtub full of water: water molecules bounce off one another in random directions until you remove the plunger. Once water starts racing down the drain, increasing the fluid's kinetic energy, a whirlpool emerges. In that whirlpool, order materializes; the molecules in the whirlpool have velocities similar in both magnitude and direction to that of neighboring molecules, and these correlations are the primitive origins of macroscopic information. To understand not only the formation but the endurance of order, we need the second trick: the existence of solids. Solid objects, such as DNA, preserve order for long periods. Without them, information would be too evanescent to last, recombine and grow.

But to explain the emergence of more complex forms of or-

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der (such as the information embodied in a city or economy) or the creation of order that gave rise to the life and societies of our planet, we need the third trick: the capacity of matter to compute. A tree, for example, is a computer that knows in which direction to grow its roots and leaves. Trees know when to turn genes on and off to fight parasites, when to sprout or shed their leaves and how to harvest carbon from the air via photosynthesis. As a computer, a tree begets order in the macrostructure of its branches and the microstructures of its cells. We often fail to acknowledge trees as computers, but the fact is that trees contribute to the growth of information in our planet because they compute.

CRYSTALLIZED IMAGINATION

ANOTHER THING WE LEARN FROM thinking of our planet as a hard drive is more surprising: despite the forces arrayed against the emergence of order, information gradually grows. Earth's hard drive is fuller now than it was yesterday or a billion years ago. In part, it is fuller because of life's emergence: biomass contains a great deal of information. But the growth of order on Earth also stems from the production of cultural information.

To see why, let us compare the apples that grow on trees with the Apples we carry in our pockets and use to check our e-mail. For our purposes, we are interested in the origin of the physical order embodied in each object. The first apple embodies order that existed in the world prior to humans. There were apples before we had a name for apples, a price for apples or a market for apples. The second Apple is different because it is an object that existed first in someone's head and then, later, in the world. It is a solidified piece of order that emerged first as imagination. As we will see, objects of this kind are particularly special.

Species that can imagine objects and then create them have important advantages over other animals. The real yet imaginary objects that pervade our economy augment us because they give us access to the practical uses of knowledge and know-how embodied in the nervous systems of other people. Consider a tube of toothpaste. Most people use toothpaste every day, but they do not know how to synthesize sodium fluoride, the active ingredient in toothpaste. That lack of knowledge, however, does not exclude them from benefiting from the *practical uses* of the understanding needed to synthesize sodium fluoride. People make practical uses of others' knowledge through products—which are, in effect, solidified pieces of imagination. Products augment us, and markets make us not only richer but also wiser.

The problem is that creating products is not easy. It often requires collaboration among large numbers of people. To contribute to the growth of information, people need to form networks with the ability to *compute* products. We need networks because the computational capacities of systems, just like their information-storing capacities, are finite. Biological cells are finite computers that transcend their limitations through multicellularity. People are also limited, and we transcend our finite computational capacities by forming social and professional networks. Economies are distributed computers that run via the hardware we know as social networks. Ultimately it is this reembodiment of computation—from cells to people and to economies—that makes the growth of complex forms of information possible but also challenging.

LIMITS OF GROWTH

THE FINAL THING this thought experiment tells us is that the ability of human networks to create information is severely constrained. Forget all the talk about big data: from a cosmic perspective, we are creating a surprisingly small amount of information (even though we burn enough energy in the process to have liberated the carbon that is warming up our planet).

Our information-creation capacity is limited in part because our ability to form networks of people is constrained by historical, institutional and technological factors. Language barriers, for instance, fracture our global society and limit our ability to connect humans born in distant parts of the globe. Technological forces can help reduce these barriers. The rise of air travel and long-distance communication has reduced the cost of distant interactions, allowing us to weave networks that are highly global and that increase our capacity to process information. Still, these technologies are no panacea, and our ability to process information collectively, while larger than in previous decades, remains small.

So how will the growth of information on Earth evolve in the coming centuries? An optimistic view is that the globalizing forces of technology and the fall of parochial institutions, such as patriotism and religion, will help erode historical differences that continue to inspire hate among people from different linguistic, ethnic, religious and national backgrounds. Meanwhile technological changes will deliver an age of hyperconnectivity. Electronics will evolve from portable to wearable to implantable, delivering new forms of mediated social interactions.

For millennia, our species' ability to create information has benefited from our ability to deposit information in our environment, whether by building stone axes or by writing epic poems. This talent has provided us with the augmentation and coordination needed for our computational capacity to increase. We are in the midst of a new revolution that has the potential to transform this dynamic and make it even more powerful. In this millennium, human and machine will merge through devices that will combine the biological computers housed between our ears and the digital machines that have emerged from our curious minds. The resulting hyperconnected society will present our species with some of the most challenging ethical problems in human history. We could lose aspects of our humanity that some of us consider essential: for example, we might cheat death. But this merger between our bodies and the information-processing machines our brains imagined might be the only way to push the growth of information forward. We were born from information, and now, increasingly, information is being born from us. SA

MORE TO EXPLORE

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FROM OUR ARCHIVES

Black Hole Computers. Seth Lloyd and Y. Jack Ng; November 2004.

ADAPT OR DIE:
Sitka spruce in British Columbia may need to borrow genes from trees in warmer climates.

SUSTAINABILITY

FORESTS ON THE MARCH

Trees can't walk to a better place as climate worsens. So scientists are relocating helpful genes instead

By Hillary Rosner

Hillary Rosner is a freelance writer based in Colorado. She has written for *National Geographic*, the *New York Times* and *Wired*, among other publications.

IN A FIELD IN VANCOUVER, ACROSS THE ROAD FROM A ROW OF TIDY WHITE TOWNHOMES, roughly 500 bushy Sitka spruce trees climbed toward the sun. On a spring day in 2013 the trees, triangle-shaped with tightly packed, deep-green needles, were crammed shoulder to shoulder—or, in some cases, shoulder to waist. Although the spruces were all planted at the same time, seven years earlier, their height varied like primary school children assembled for a group photograph.

The smallest trees, around two feet tall, hailed from Kodiak Island, Alaska; the tallest, at nearly seven feet, originated in Oregon. Height was not the only visible difference. The spruces from Alaska produced buds a full three months earlier—an entire season—than those from Oregon. The Alaska trees also stayed green and healthy no matter how low the temperature dropped.

The spruces had been rooted in this field, at one end of the University of British Columbia's rambling campus, as an experiment to highlight how trees adapt to local environments. That trees match their habitats may sound obvious. But the details are important because of a looming threat: those habitats are changing as the planet warms—and trees can't exactly get up and walk to a new home. If a species cannot keep pace with a changing climate, it is doomed.

Because the trees themselves cannot relocate, scientists are exploring a novel solution: relocating the plants' DNA. That is why Sally N. Aitken planted the spruce garden. Aitken, director of the university's Center for Forest Conservation Genetics, believes saving the forests of British Columbia—and others around the world—may hinge on a practice called assisted gene flow. It could help species adapt to future conditions by moving organisms with particular traits from one part of their natural range to another. The tree from Oregon and the tree from Alaska just might have some genes that could help each other out. But without intervention, they would never meet.

Like an arboreal matchmaker, a forester could take seeds from spruces or lodgepole pines at a low elevation, say, and plant them farther upslope. As temperatures on the higher slopes warmed, the relocated trees would grow up and breed with their local counterparts, spreading their warm-adapted genes throughout the area and thus helping the forest adjust. Assisted gene flow could give species an evolutionary hand.

But you can't simply take a tree from Oregon, plant it 1,000 miles away in northern British Columbia and wait for the mercury to rise. The reasons that you can't come from the same local genetic adaptations that make the gene-flow idea attractive. Lodgepole pines, for instance, grow in different regions throughout much of the Canadian province. Their genes help some trees better tolerate heat or cold or drought or fend off local diseases or pests. If an Arctic cold front moves through Vancouver, hitting transplants from warmer regions, they will suffer. "We need to shift these things starting with baby steps," Aitken says. "The changes projected over the next few decades are really big, but we still have a lot of year-to-year and week-to-week and month-to-month variation that those trees have to survive."

Figuring out how to match today's seeds with tomorrow's climates is no easy task. But in British Columbia, where forestry accounts for a third of all exports and commercial forests make up nearly half of the total forest cover, it is vital. Provincial law requires that forests be replanted after logging, to bolster future timber supplies and healthy ecosystems. Roughly 250 million seedlings are planted annually. Just where those seeds should come from and how far they can or should be moved is a complicated—and pressing—question. Do it wrong, and you could be dooming the forests for decades to come.

The Sitka spruce experiment, which involved trees from 14 different locations ranging from central California up to Alaska, was Aitken's small proof of concept for a larger effort to avoid this type of fatal misstep. The research yielded 35 segments of DNA associated with cold tolerance and bud timing.

IN BRIEF

Forests adapt genetically to survive in local conditions, but climate is changing faster than trees can adjust.

To prevent forest death, scientists are moving trees with genes tied to water use and heat tolerance near other trees that need this DNA so they can breed.

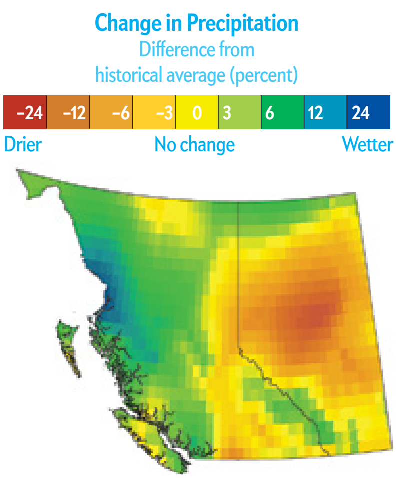
Assisted gene flow, as the strategy is called, is being tested on trees from different climate zones in British Columbia.

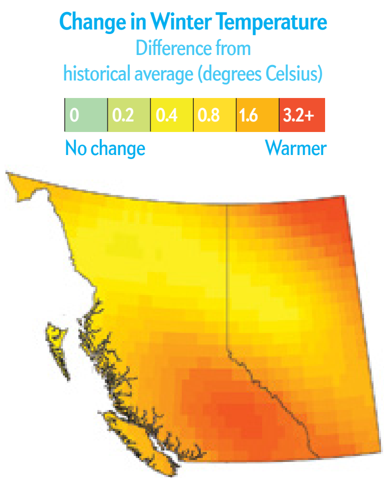
PRECEDING PAGES: TJ WATT

FOREST ECOLOGY

Weather Trends for Trees

Scientists compared the past with the present to figure out recent climate trends in British Columbia and Alberta and whether they depart from what trees experienced during the latter half of the 20th century. Researchers gathered direct observations from weather stations throughout the provinces between 1961 and 1990. The scientists compared this baseline with averages from a more recent period, 1997 through 2006. For the recent period, they noted whether the averages were wetter, drier or warmer or did not change from the earlier averages. They learned that the climate has become much wetter along the Pacific coast, which the researchers link to outbreaks of a previously rare pine needle blight. At the same time, it has become drier in the interior, which may account for spruce and aspen deaths there. Winters have been warmer all over the provinces, allowing the tree-killing mountain pine beetle to spread to more forests. (Methods for this analysis were published in the journal *Agricultural and Forest Meteorology* in 2009.)





Now Aitken and her team are sifting through more tree genomes to find genes responsible for proteins that are linked to other environmental traits. Their hope is that beneficial versions of these genes—called alleles—would spread through populations that need the traits, in rough synchrony with the climate changes that make those genes useful.

The larger project, called AdapTree, could help pave the way for future assisted gene-flow projects around the world, work that could in turn help other species that are key ecosystem architects. Corals in the sea, for instance, harbor food and provide shelter for all kinds of other species. Researchers in the U.S., Abu Dhabi, Qatar and Australia have suggested moving corals from the Persian Gulf to the Indo-Pacific to help spread genes for heat tolerance. And in the American Midwest, efforts to restore grasslands have shown that it is important that replanted seeds come from a broad range of habitats.

Aitken and Michael C. Whitlock, a population geneticist in the university's zoology department, coined the phrase "assisted gene flow" in a 2013 paper. Over the past decade scientists and conservationists have been arguing over a more grandiose idea, "assisted migration," which generally refers to moving species greater distances, outside their natural ranges. But assisted gene flow within a species' range is a more measured approach with genetic rigor at its heart. By the time AdapTree wraps up in several years, researchers will have assembled DNA sequence information for 12,000 lodgepole pine and spruce trees from more than 250 populations across British Columbia and Alberta.

CLIMATE ZONES

THOSE TREES are already feeling the effects of a changing climate. Back in the 1970s, British Columbia's government produced a climatic map of the province, organizing it into a series of biogeoclimate zones. That map has underpinned forest planning in western Canada for four decades, helping to govern which seeds can be planted where. Today, though, thanks to climate change, nearly a quarter of the map is obsolete. Some zones have moved, and others have dwindled dramatically. High-elevation zones and some interior plateaus have already lost around half their habitat—and could shrink by more than 80 percent by 2100. Seeds of trees that once would have thrived in a particular area might today be unable to even grow there. Zones may morph into ecosystems that are fundamentally different from what existed before, although exactly how much change is required before an ecosystem is "fundamentally different" is unclear and controversial.

Whether a particular population can adapt to change depends in part on how quickly the organism reproduces. Each new generation represents a chance to acquire useful new traits. So a pine beetle, which reproduces quickly, has a much better chance of adapting than a tree, which is long-lived and slow to reproduce. A single bug may witness no change at all during its life span. A tree, though, has a front-row seat to global warming.

A stand of forest is most at risk during its first 20 years of life. Once the trees are established, they become far more resilient, "able to stick around for a while," says Brad St. Clair, a research geneticist at the U.S. Forest Service in Corvallis, Ore. But in the era of global warming, local conditions can change considerably over those two crucial decades.

"If you're going to move things to higher elevations so they'd be adapted to future climates," St. Clair says, "then they have to be adapted to cold-hardiness now." In other words, if you move warm-adapted trees now into a zone that is projected to warm in the future, those trees could be in short-term trouble because the zone is still cold today.

"We've got a moving target," Aitken admits. "Do we want to best match trees with climate when they're seedlings? Or 10 years old? Or 30 years old?" One way to manage risk is to increase diversity—which might mean mixing local and nonlocal seeds.

Maps by Andreas Hamann

“You don’t want to do the same thing on every hectare of ground. You can’t plan around a single climate change scenario.”

Assisted gene flow may be a good way to bulk up a forest’s genetic diversity, sprinkling its gene pool with the ingredients that give trees a boost. As the environment shifts, some trees may suffer in the short term, but other trees will have genetic material that could help the forest weather tough times. “As those individuals that are more fit reproduce more,” Aitken says, “we expect populations to start expanding again.” The critical element, she says, is maintaining enough healthy trees to mate and survive while the process of adaptation unfolds.

Aitken, an avid backpacker and backcountry skier who owns a cabin in the woods of central British Columbia, hopes her work will help set new, smarter forest policy. She believes that if we do not begin practicing assisted gene flow, tree populations may begin to fail at the far northern or southern edges of species’ ranges. “Trees might persist a long time, but they might stop reproducing,” she says. “They’d be evolutionarily toast.” They would become, she adds, a “land of the living dead.” What’s worse, they would hog space and sunlight that seedlings desperately need. Closer to the middle of a range, things would be a bit less dramatic. But trees might still grow more slowly or have trouble surviving. “Does that mean the populations there are just going to die?” Aitken asks. “Probably not. There’s a lot of variation within populations. The species aren’t going to go extinct, but I imagine you’d have pretty unhealthy-looking forests in the meantime.” The poor health would harm other plants and animals because trees anchor entire ecosystems, providing food and shelter, regulating water flow and preventing soil erosion.

Around the world, Aitken says, “there has been very little attention paid to the movement of individuals within existing species ranges.” The ecological risks are lower than transplanting truly foreign trees because such foreigners are not already part of the ecosystem, even though they may possess some desirable traits.

SEEDS OF CHANGE: The AdapTree experiment gathers seeds from different habitats (*1*). Pine seedlings grown in the project’s greenhouse (*2*) show variation in shape (*3*). Some needles are tested with a probe (*black rod*) to see whether they can resist freezing temperatures (*4*).

There are still risks to a gene-flow approach. It could, for instance, add local gene variants that would actually harm a larger population’s chance for survival. “There is a risk that you could be introducing unwanted alleles,” says Andrew Weeks, a geneticist at the University of Melbourne. But the problem would likely correct itself, he adds. “That’s the beauty of natural selection, which will weed out these variants. By increasing the gene pool, you are giving the population the best chance for the future.”

With British Columbia’s forests worth $10 billion a year—as well as providing vital services such as preventing floods and soil erosion—doing nothing may pose an even greater risk. British Columbia has already seen what global warming can do to forests. Since the mid-1990s beetle invasions and wildfires, both linked to warming temperatures, have destroyed millions of acres of forest and consumed hundreds of homes. “We’ve had lots of wake-up calls here in terms of climate change,” says Greg O’Neill, a research scientist at British Columbia’s Ministry of Forests, Lands and Natural Resource Operations. The insects and fires, O’Neill says, left people in the province “quite cognizant of climate change—and not that it’s some abstract thing in the future, but it’s already happening.”

The losses jolted the provincial government into action. In 2009 British Columbia began revising its rules on moving seed. That same year O’Neill began an assisted migration trial for the province’s forests, hoping to determine whether, where and how foresters might plant completely different species after harvesting. At 48 sites throughout Canada and the western U.S.—from Whitehorse to Sacramento—researchers planted 15 species of commercially important trees, moving them from their home range and, in some cases, relocating them thousands of miles away.

The extreme migration, O’Neill says, is merely a research tool, a way to provide a better overall picture of how the trees will fare. It is not intended as a guide for long-distance moves.

COURTESY OF JACK WOODS *AdapTree project, University of British Columbia* (seeds);
COURTESY OF CONNOR FITZPATRICK *AdapTree project, University of British Columbia* (greenhouse)

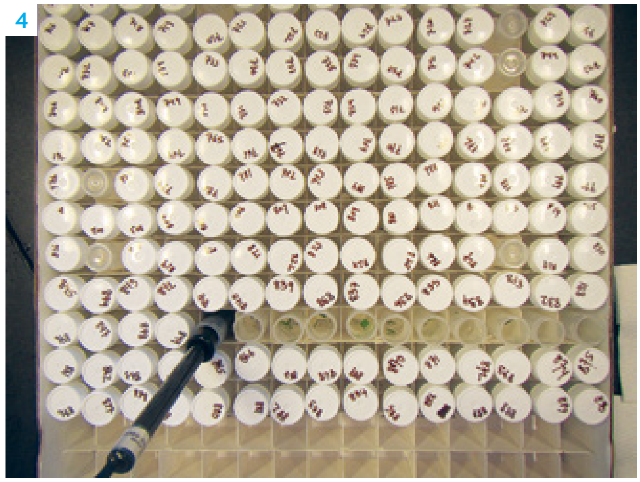
SCIENTIFIC AMERICAN ONLINE Watch biologist Sally N. Aitken explain moving genes in forests at ScientificAmerican.com/aug2015/moving-genes

Any actual changes in planting patterns will be incremental. "Something like 'Do not move your trees downhill' or 'Do not move your trees south,' " he says. There is a weather station at each site, and the study will show how the growth and survival of the seedlings relate to the local conditions. Then, O'Neill says, scientists will be able to predict how the trees will respond to climate change.

The genetic analysis of AdapTree offers a complementary way to predict how the trees will fare. Researchers on the sprawling project pored over DNA sequences from millions of locations in the genomes of interior spruce and lodgepole pine trees. They developed a quick screening method—similar to that used by the human genome screening business 23 And Me—that looks at roughly 50,000 short strings of genetic code, known as single nucleotide polymorphisms, or SNPs. With that done, they are "digging in," as Aitken puts it, trying to zero in on the specific polymorphisms that match a tree to its home base. Initial work on 600 young trees in the AdapTree project identified genetic markers that explain many of the differences in how trees from various regions grow and cope with cold, heat and varying amounts of water.

3

4



COURTESY OF JACK WOODS *AdapTree project, University of British Columbia (needles)*; COURTESY OF PIA SMETS *AdapTree project, University of British Columbia (vials)*

The raw genetic data from AdapTree are dizzying. Printed on both sides of sheets of 8 ½ by 11 paper, Aitken notes, the stack would rise about 150 kilometers. And that is only part of the information. Researchers are now looking at how the genes actually function—how their instructions are carried out—when the trees encounter stresses such as drought or high temperatures.

FORESTS OF THE FUTURE

A FEW DEGREES of latitude south, specialists in the U.S. Forest Service are beginning to weigh the pros and cons of assisted gene flow. "Where we're at is a lot of talk and discussion," St. Clair says. In the U.S., foresters historically did not focus on specific climate variations within zones where they collected and planted seeds. Moving seeds in a zone did not appear to involve enough temperature change to affect plant health.

Now foresters generally agree they need to get much better at moving seed. For as long as people have been planting trees, we have been relocating seed across rivers, villages, continents or oceans. "If you go back far enough, people used to move seed around all the time, and you'd often end up with failed plantations because people had no idea what they were doing," says Glenn Howe, a forest geneticist at Oregon State University. Partly as a result of those failures, over time the forestry community developed an aversion to risk. In the western U.S., seed zones, which guide how far seeds can be moved for planting, are narrow and conservative. "That's probably appropriate in a static climate," Howe says. "But with climate change, a very conservative approach could be a problem."

British Columbia is forging ahead, but challenges remain. Beyond the scientific problem lie management issues. The government's provincial tree seed center contains enough seed for more than six billion trees; you can't change that inventory overnight. Nor can you change human behavior: researchers will need to convince resource managers to trust in genomic data, something they cannot see for themselves in the field. It is crucial that all those nucleotide polymorphisms and sequence data "translate into a forester's lexicon," Aitken says.

Because ultimately all those strands of DNA make up living, breathing trees—the ones we depend on to construct our built environments as well as our natural ones. To thrive in a changing world, some of those trees may need to branch out into new territory. And to do that, they are going to need our help. SA

MORE TO EXPLORE

Placing Forestry in the Assisted Migration Debate. John H. Pedlar et al. in *BioScience,* Vol. 62, No. 9, pages 835–842; September 2012.

Assisted Gene Flow to Facilitate Local Adaptation to Climate Change. Sally N. Aitken and Michael C. Whitlock in *Annual Review of Ecology, Evolution, and Systematics,* Vol. 44, pages 367–388; November 2013.

Evaluation of Demographic History and Neutral Parameterization on the Performance of F_{ST} Outlier Tests. Katie E. Lotterhos and Michael C. Whitlock in *Molecular Ecology,* Vol. 23, No. 9, pages 2178–2192; May 2014.

AdapTree project: http://adaptree.forestry.ubc.ca

FROM OUR ARCHIVES

The American Chestnut's Genetic Rebirth. William Powell; March 2014.

scientificamerican.com/magazine/sa

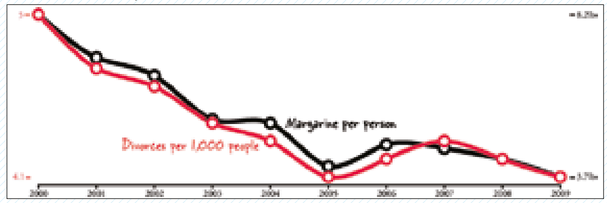
MORE TO EXPLORE For more book recommendations, visit ScientificAmerican.com/aug2015/recommended

Spurious Correlations

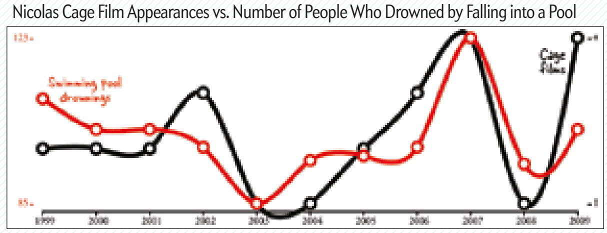
by Tyler Vigen.
Hachette Books, 2015 ($20)

"Correlation does not equal causation" is an oft-repeated, yet oft-forgotten, maxim. When two quantities happen to vary together, people are apt to think one depends on the other, whether or not they do. Vigen, a Harvard Law School student, illustrates that point in this hilarious and illuminating collection of completely coincidental correlations—such as the number of films Jennifer Lawrence appears in yearly and the gross domestic product of Australia (97.8 percent correlation) and the annual rate of shark attacks compared with that of tornadoes (77.4 percent). Beyond the humor, Vigen makes a serious point: spurious connections are becoming easier to find thanks to the increasing availability of large data sets and the tools to mine them. As science becomes more and more intertwined with "big data," researchers must fight the urge to ascribe meaning to every association they discover.

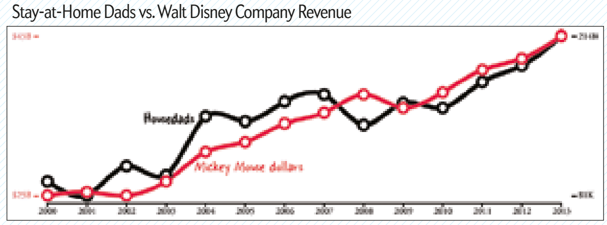
Margarine Consumption vs. Divorce Rate in Maine



Nicolas Cage Film Appearances vs. Number of People Who Drowned by Falling into a Pool



Stay-at-Home Dads vs. Walt Disney Company Revenue



Life's Greatest Secret: The Race to Crack the Genetic Code

by Matthew Cobb.
Basic Books, 2015 ($29.99)

After Catholic monk Gregor Mendel discovered the laws of inheritance—how traits are passed on from parents to offspring—in the 1860s, his work was ignored for 35 years. But in 1900 three scientists rediscovered Mendel's findings and popularized them, spawning what zoologist and science historian Cobb calls "the century of genetics." Cobb goes on to recount the way researchers gradually cracked the genetic code—and, indeed, how they came to think of it as a code in the first place. The idea, finally described in 1953 by James Watson and Francis Crick, that the ordering of chemical bases on DNA contains the instructions for life was not obvious, and the tale of its discovery takes many turns. By thinking of the genetic code as a repository of information, Cobb argues, the study of genetics helped to usher in the modern information age.

Modern Romance

by Aziz Ansari, with Eric Klinenberg.
Penguin Press, 2015 ($28.95)

Among the facets of daily life that the Internet has irrevocably altered is certainly the search for love. Stand-up comedian Ansari is an unlikely but perfect tour guide through this changed landscape. He not only shares personal anecdotes (such as how waiting for a text message response from a date induced existential panic) but also parses data gleaned through a partnership with New York University sociologist Klinenberg. The two analyzed numerous research findings, convened focus groups in eight cities around the world and interviewed hundreds of people looking for romance, along with numerous scientists. Ultimately they found that technology explains only part of the recent transformation in how people find mates; rather cultural shifts have changed what singles look for in a match—a perfect soul mate instead of simply a compatible partner—and what they are willing to go through to find it.

Genius at Play: The Curious Mind of John Horton Conway

by Siobhan Roberts.
Bloomsbury, 2015 ($30)

Mathematician John H. Conway's name pops up all over the mathematics world—group theory, game theory, knot theory, abstract algebra, geometry—and in the pages of this magazine, where he was frequently featured in Martin Gardner's Mathematical Games column. It was there that his most famous creation, Conway's Game of Life—a set of rules for propagating a pattern that generates incredible complexity—made its world debut. Science journalist Roberts's new biography of Conway demonstrates how the man's playfulness and originality has fed into the creativity and intelligence of his ideas. The tome resonates with Conway's voice—which gets its own special font—and his discussions with the author dictate the story's structure and provide the narrative's best glimpses into how his mind darts and weaves. *—Sarah Lewin*

TYLER VIGEN, COURTESY OF HACHETTE BOOKS

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

The Meaning of Life in a Formula

Can science help us overcome the terror of existence?

Harvard University paleontologist Stephen Jay Gould, who died in 2002, was a tough-minded skeptic who did not suffer fools gladly when it came to pseudoscience and superstition. Gould was a secular Jew who did not believe in God, but he had a soft spot for religion, expressed most famously in his principle of NOMA—nonoverlapping magisteria. The magisterium (domain of authority) of science "covers the empirical realm: what is the universe made of (fact) and why does it work this way (theory)," he wrote in his 1999 book *Rocks of Ages: Science and Religion in the Fullness of Life.* "The magisterium of religion extends over questions of ultimate meaning and moral value."

In part, Gould's motivations were personal (he told me on many occasions how much respect he had for religion and for his many religious friends and colleagues). But in his book, he claimed that "NOMA represents a principled position on moral and intellectual grounds, not a merely diplomatic solution." For NOMA to work, however, Gould insisted that just as "religion can no longer dictate the nature of factual conclusions residing properly within the magisterium of science, then scientists cannot claim higher insight into moral truth from any superior knowledge of the world's empirical constitution."

Initially I embraced NOMA because a peaceful concordat is usually more desirable than a bitter conflict (plus, Gould was a friend), but as I engaged in debates with theists over the years, I saw that they were continually trespassing onto our turf with truth claims on everything from the ages of rocks and miraculous healings to the reality of the afterlife and the revivification of a certain Jewish carpenter. Most believers hold the tenets of their religion to be literally (not metaphorically) true, and they reject NOMA in practice if not in theory—for the same reason many scientists do. In his 2015 penetrating analysis of *Faith vs. Fact: Why Science and Religion are Incompatible,* University of Chicago evolutionary biologist Jerry A. Coyne eviscerates NOMA as "simply an unsatisfying quarrel about labels that, unless you profess a watery deism, cannot reconcile science and religion."

Curiously, however, Coyne then argues that NOMA holds for scientists when it comes to meaning and morals and that "by and large, scientists now avoid the 'naturalistic fallacy'—the error of drawing moral lessons from observations of nature." But if we are not going to use science to determine meaning and morals, then what should we use? If NOMA fails, then it must fail in both directions, thereby opening the door for us to experiment in finding scientific solutions for both morals and meaning.

In *The Moral Arc,* I give examples of how morality can be a branch of science, and in his 2014 book *Waking Up: A Guide to Spirituality without Religion,* neuroscientist Sam Harris makes a compelling case that meaning can be found through the scientific study of how the mind works (particularly during meditation and other mindful tasks), noting that "nothing in this book needs to be accepted on faith." And Martin Seligman's pioneering efforts to develop a science of positive psychology have had as their aim a fuller understanding of the conditions and actions that make people happy and their lives meaningful.

Yet what if science shows that there is no meaning to our lives beyond the purposes we create, however lofty and noble? What if death is the end and there is no soul to continue after life? According to psychologists Sheldon Solomon, Jeff Greenberg and Tom Pyszczynski, in their 2015 book *The Worm at the Core: On the Role of Death in Life,* the knowledge that we are going to die has been a major driver of human affairs and social institutions. Religion, for example, is at least partially explained by what the authors call terror management theory, which posits that the conflict between our desire to live and our knowledge of our inevitable death creates terror, quelled by the promise of an afterlife. If science takes away humanity's primary source of terror management, will existential anguish bring civilization to a halt?

I think not. We do live on—through our genes, our loves, our friends and our contributions (however modest) to making the world a little bit better today than it was yesterday. Progress is real and meaningful, and we can all participate. SA

SCIENTIFIC AMERICAN ONLINE
Comment on this article at ScientificAmerican.com/aug2015

Illustration by Izhar Cohen

The ongoing search for fundamental farces

Steve Mirsky has been writing the Anti Gravity column since a typical tectonic plate was about 34 inches from its current location. He also hosts the *Scientific American* podcast Science Talk.

The Cheese Eyes Have It

Holes in Swiss cheese finally give up their gaseous secrets

About two decades ago Swiss geneticists were trying to figure out how a few vital genes exerted master control over the development of fruit flies. In the course of their work, they managed to get a fly to grow numerous eyes all over its body. Sure, the information is crucial for our understanding of how an individual changes from a single fertilized egg into a differentiated organism, but little to no market exists for the disturbing *Drosophila*.

This year a different group of Swiss scientists figured out another vexing eye problem: exactly what causes the formation and development of the numerous eyes (what we laypeople call holes) in Emmental (what we laypeople call Swiss) cheese. The information is crucial for our understanding of how to create cheeses with the right number and size of holes. And billions of dollars in revenues are at cheese-stake in quiches, fondues and sandwiches alone.

To give you an idea of the scope of the Emmental effort, it took 13 researchers at three different Swiss facilities—Agroscope's Institute for Food Sciences, Empa's Center for X-ray Analytics and the Lucerne University of Applied Sciences and Arts—to come up with the study, which was published in the *International Dairy Journal* with the title "Mechanism and Control of the Eye Formation in Cheese." The history is a little unclear, but it looks like it took only one guy, the late Tom Nugent, coach at the Virginia Military Institute around 1950, to come up with the mechanism and control of the I-formation in football.

The connection between the two disciplines can be seen in Green Bay, Wis., where Packers fans proudly recognize their state's dairy prowess by wearing large wedges of faux cheese on their heads. Cheddar may outsell Swiss at the grocery store, but the hat cheese, like the head wearing it at the frozen tundra of Lambeau Field, clearly has holes in it.

The journal article points out that "the size of the eyes of first-quality cheese should be between the size of a cherry … and a walnut." (To use language more familiar to this magazine's readership, that's between the size of a large ureterovesical cyst and an adult's prostate.) But different people prize different eyes. "Italian consumers prefer Emmental cheese with walnut-sized eyes," the study authors note, "whereas commercial manufacturers of sliced cheeses ask for cheese with smaller eyes and higher eye numbers." Thus, you want to control the eyes.

Bacteria do most of the work in cheese making. They produce carbon dioxide gas, forcing the expansion of eyes. If you manage to make what is actually called blind Swiss cheese—no eyes at all—the gas buildup causes slits or splits that reduce quality. Besides, Swiss cheese without holes is a semiotic disaster.

But what makes an eye start to form? Cheese whizzes assumed for the past century that some tiny particle acted akin to the seed of a dust mote, around which a drop of rain forms in a vapor-saturated air mass. The Swiss scientists thus thought, Hay! Dairy farms have lots of hay, and hay dust "could act as highly effective eye nuclei."

They mixed various amounts of hay particles into embryonic Emmentals and found that they could "control the number … and size of the eyes in cheese in a dose-dependent manner." The data should open the eyes of cheese makers worldwide, figuratively and possibly literally.

The intrepid investigators also unintentionally solved a problem that's been bothering Swiss cheese fans: over the past few decades the holes have been getting fewer and smaller. Now we can surmise that better hygienic conditions have been limiting contamination by plant particulates. The result has been the counterproductive reduction in the size and frequency of the holes. In other words, when it comes to cheese, there are none so blind as those that will not seed. SA

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Illustration by Matt Collins

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America's Lost Masterpiece

The $100 Union

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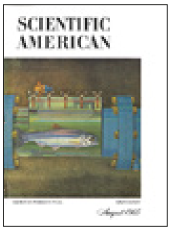
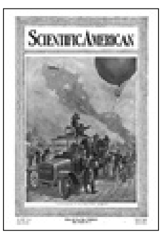


August 1965

Infrared Astronomy

"Researchers from the California Institute of Technology used the 100-inch reflecting telescope on Mount Wilson to make measurements of the carbon dioxide absorption bands in the photographic infrared radiation reflected from Mars; they concluded that carbon dioxide is less plentiful than had been indicated by earlier and less accurate measurements. This implied that the pressure of the atmosphere at the surface of Mars is only about 0.37 pound per square inch, or 2.5 percent of the earth's atmospheric pressure of 14.7 pounds per square inch at sea level. The Martian atmosphere therefore may be too rarefied to support either a winged vehicle or a parachute, both of which had been considered for landing instrument capsules from spacecraft."



August 1915

Typhoid Vaccine

"During the Franco-German war [1870–1871] thousands upon thousands of soldiers died from typhoid fever. The freedom from this disease in the present conflict is due in part to a better understanding of the principles of sanitation, and a great deal of it is due to the work of the man in the laboratory. Years of painstaking lab research have resulted in the anti-typhoid vaccine, which is saving the armies of the world from typhoid fever epidemics. During the year 1911 typhoid vaccination was made compulsory in the United States Army; the value of this vaccination may be seen in the fact that in 1912 the death rate from typhoid fever in the United States was 16.5 per hundred thousand and in the United States Army the rate was 0 per hundred thousand."

World War I at Sea

"Germany, realizing that her naval ships were shut up securely in her own ports, that her merchant fleet was being swept from the high seas, and that she was cut off from the greater part of her supplies by sea, had but one form of warfare left open for herself, namely, the secret warfare by mine and submarine [*see illustration*]. It is with the submarine that Germany has scored her greatest success."

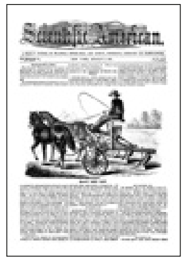
Images from the conflict at sea during World War I are at www.ScientificAmerican.com/aug2015/navy-1915

Weather at the Movies

"Weather forecasts on motion-picture screens were first shown in Birmingham, Ala., in January, 1912, since which time their display in this manner has been extended to 15 cities and at 27 moving-picture theaters. The Weather Bureau is willing to furnish forecasts for this purpose wherever they are desired, but the demand for them is limited by the fact that most moving-picture shows do not open until an evening hour subsequent to the time at which the same forecasts appear in the afternoon newspapers."

SUBMARINE WARFARE: A hunter quietly stalking its prey, 1915

SCIENTIFIC AMERICAN, VOL. CXIII, NO. 6; AUGUST 7, 1915



August 1865

Picking Cotton

"Since the war has ended the attention of many persons has been drawn to the cultivation of cotton with the laudable design of once more stocking the market and starting factories, so that the needs of the people shall be supplied. Of course the old-time methods of growing this staple are unsuited to the spirit which now directs operations. This listless and slovenly culture is to give way before an energetic, methodical and business-like mode, so that two bolls shall grow where but one did formerly. Machinery in general is wanted, but for one special machine, above all others, there is great need. That is one for picking cotton."

Successful mechanical pickers were not employed for another 80 years.

Rent Was Too Darn High

"It is one of the social evils of large cities that dwellings for persons of small means are not to be had. There are none who feel this more keenly than mechanics. After toiling hard all day in the noise and clatter of the factory, they need a clean and quiet home to refresh them for the labor of the day coming. But, in New York, and in most large cities, this is a thing unattainable. Every mechanic who desires to live comfortably pays rent far beyond his means; or if he chooses the other alternative—a low rent—the only places offered are crowded rooms, high up above the street, and reeking with vermin and stench."


MY MOM DIDN'T HAVE MANY OPTIONS.
TODAY'S LUNG CANCER PATIENTS DO.
Twenty years ago, my mother was diagnosed with lung cancer. She had very few places to turn, and lost a difficult struggle.
Today, we are on the brink of real breakthroughs in lung cancer research and there are significantly improved treatment options.
And yet, more than 30% of all lung cancer patients still don't know about the therapies, specialists, and clinical trials available to them.
Lung cancer is a formidable foe, but we are finding new ways to fight it. Please visit SU2C.org/LungCancer for questions to ask your health care professional and to learn about options that may be right for you.
Tony Goldwyn
Stand Up To Cancer Ambassador
Bristol-Myers Squibb
STAND UP TO CANCER®
SU2C.org/LungCancer
Photo Credit: Kevin Lynch
Stand Up To Cancer is a program of the Entertainment Industry Foundation (EIF), a 501(c)(3) charitable organization.

Drug-Resistant Stomach Bug

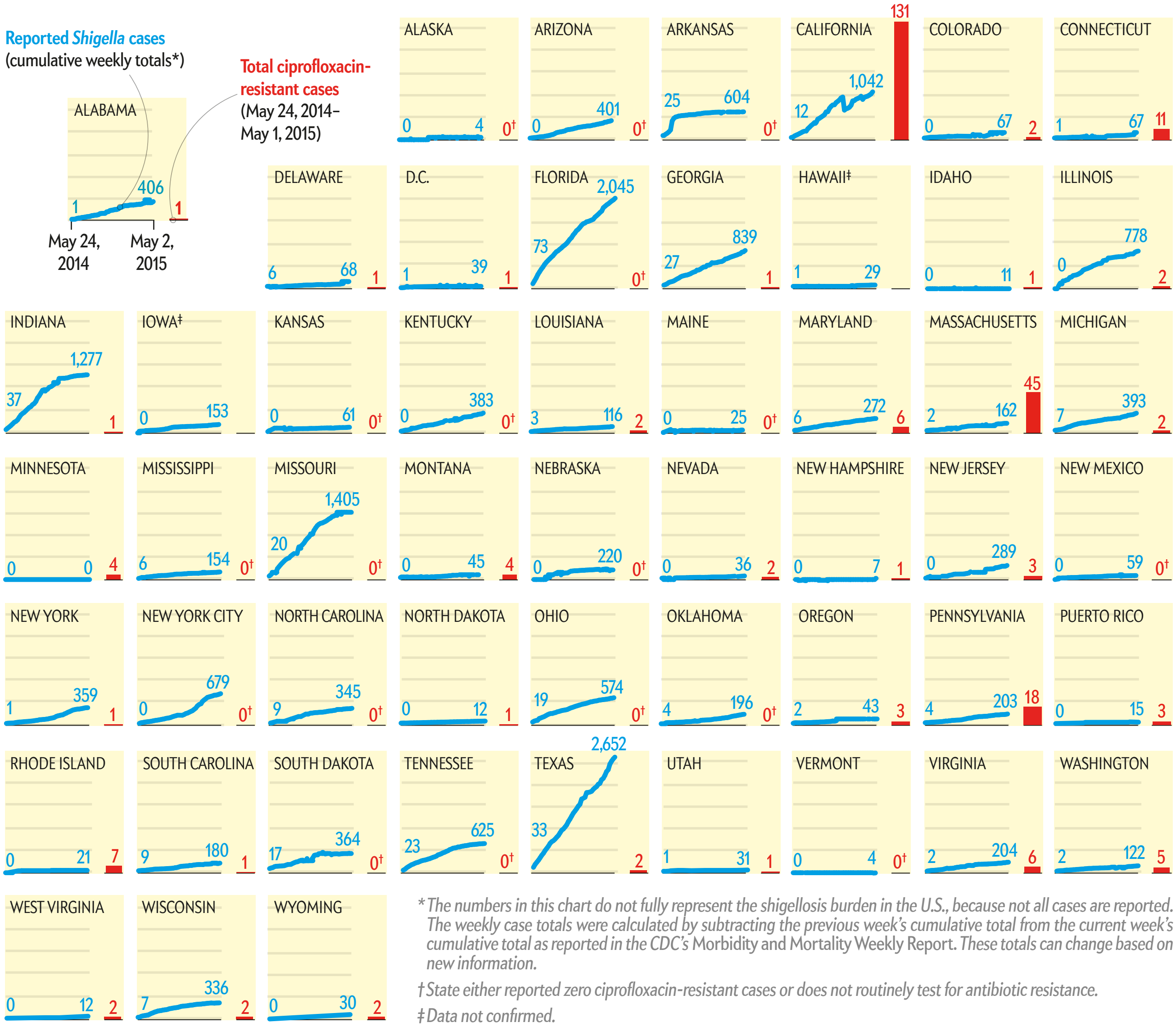
A tough-to-treat strain of *Shigella* has established a foothold in the U.S.

The kinds of bacteria that can cause diarrheal ailments such as food poisoning lurk all around us. These germs, which include *Escherichia coli* and *Shigella,* can be especially easy to pick up when traveling internationally, as well as in places, such as a children's day care, that are hard to keep clean. In April the U.S. Centers for Disease Control and Prevention reported an outbreak of *Shigella sonnei* that has become resistant to ciprofloxacin—one of the last remaining medications in pill form that can kill that pathogen. Since then, a Scientific American investigation shows the worrisome strain is still circulating in the U.S. a year after it first emerged.

The CDC confirmed 275 cases of ciprofloxacin-resistant *Shigella* across the country between May 2014 and May 2015 and released somewhat more detailed data about confirmed reports in each state to Scientific American (*chart below*). Although these figures appear small, they almost certainly represent but a tiny fraction of the true number of ciprofloxacin-resistant cases. All *Shigella* infections are supposed to be reported to the CDC, but a lot of people who get sick do not go to the doctor. And those who do are sometimes not tested for the presence of *Shigella,* let alone drug resistance. *—Rebecca Harrington*

SCIENTIFIC AMERICAN ONLINE
To learn more about *Shigella,* visit ScientificAmerican.com/aug2015/graphic-science

Shigella Cases on the Rise



**The numbers in this chart do not fully represent the shigellosis burden in the U.S., because not all cases are reported. The weekly case totals were calculated by subtracting the previous week's cumulative total from the current week's cumulative total as reported in the CDC's Morbidity and Mortality Weekly Report. These totals can change based on new information.*

†State either reported zero ciprofloxacin-resistant cases or does not routinely test for antibiotic resistance.

‡Data not confirmed.

SOURCE: CENTERS FOR DISEASE CONTROL AND PREVENTION

Graphic by Nigel Hawtin