THE GREAT ECLIPSE OF 2017 PAGE 54 And what to expect for the next 1,000 years

SCIENTIFIC AMERICAN

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ON EDUCATION

THE NEW ORIGINS OF LIFE

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PLUS

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ON THE COVERS

When Charles Darwin suggested life on Earth began in a "warm little pond," he was not necessarily thinking of a volcanic landscape. Yet evidence from remote Australia, recounted in our story "Life Springs," indicates that ancient hot springs (*left*), geysers and calderas had the building blocks of early cells with potential to evolve. Compounds became concentrated in vesicles (*right*) made of lipids. Over time, heat and chemical energy caused the compounds in these vesicles to link into more complex molecular chains. **Illustration by Kenn Brown, Mondolithic Studios (*left*). Illustration by Mark Ross (*right*).**

COVER: CLADOGRAM DESIGNED BY DAVID HILLIS, ORIGINALLY PUBLISHED IN *LIFE: THE SCIENCE OF BIOLOGY*, 10TH EDITION. COPYRIGHT © 2014 BY SINAUER ASSOCIATES, INC. (*left*)

Photograph by Christian Rodriguez

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ON THE WEB

Interactive Eclipse Portal
Scientific American has created an interactive map of when and where to view all the central solar eclipses occurring worldwide through the year 3000.
Go to www.ScientificAmerican.com/aug2017/eclipse

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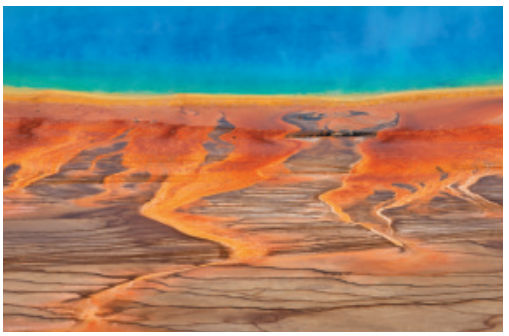
Mariette DiChristina is editor in chief of *Scientific American*. Follow her on Twitter @mdichristina

In the Beginning

There was light. But then what happened?

How did life arise on the third rocky planet orbiting the unremarkable star at the center of our solar system? Humans have been wondering about the answer to that question probably almost as long as we've been able to wonder. In recent decades scientists have made some gains in understanding the conceivable mechanisms, gradually settling on a possible picture of our origins in the oceans. The idea was that hydrothermal vents at the bottom of the seas, protected from cataclysms rending the surface four billion years ago, delivered the necessary energy and could have sustained the molecules needed.



LIFE on Earth could have arisen in places similar to the Grand Prismatic Spring in Yellowstone National Park.

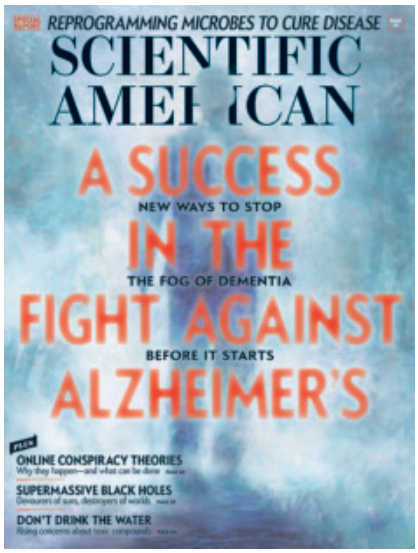
Perhaps not. Water was a necessary ingredient, surely, but that doesn't mean we sprang from oceans, according to researchers Martin J. Van Kranendonk, David W. Deamer and Tara Djokic in our cover story, "Life Springs." Oceans, they write, might have spread the needed molecules too quickly for cell membranes and functions to occur. Instead they argue, land pools in an active volcanic landscape that repeatedly dried and got wet again could have cradled the seeds of life. How could something that sounds so harsh have been beneficial, you ask? To find out, please turn to page 28.

The sun's rays provided vitality for this world. Seeing them dim temporarily, as they do during a solar eclipse, is awe-inspiring. It's been nearly a century since a total solar eclipse has crossed the U.S. from coast to coast. Starting on page 54, you'll find that "The Great Solar Eclipse of 2017," by Jay M. Pasachoff, tells you everything you need to know about this rare event. And a companion piece, "1,000 Years of Solar Eclipses," by senior editor Mark Fischetti, with illustrations by senior graphics editor Jen Christiansen and designer Jan Willem Tulp, tells you what you *will* need to know as well. I like to think that the readers of *Scientific American,* which turns 172 this month, will be enjoying the solar shows well into the future.

If they do enjoy them, it'll be because we've fostered a love of learning about the world around us. How we teach and create the right learning environments are critical to our students' success. For that reason, we've taken an evidence-based look at the concept of vouchers in education in "A Matter of Choice," by journalist Peg Tyre, starting on page 48. The concept is a keystone of the current administration's plan to revamp education, but research finds it wanting. Fortunately, there is still time to make a choice. SA

GETTY IMAGES

Illustration by Nick Higgins



April 2017

CATCHING A CONSPIRACY

In "Inside the Echo Chamber," Walter Quattrociocchi describes his and his colleagues' work on researching how conspiracy theories propagate online. The article reminds me of the elements necessary for an infection to successfully spread within a population. First, an agent must exceed a certain threshold of infectivity, a property called virulence. Second, vulnerable hosts must be available to become infected. If many in a population have acquired an immunity, then even if one person catches a given infection, it will be less likely to successfully propagate. Finally, there must be a vector or vehicle to physically spread the infectious agent. In this analogy, a certain audience may possess a host vulnerability to a given piece of misinformation, and the vehicle that spreads it is now ubiquitous in the form of social media.

We cannot remove social media—it is here to stay—and we cannot squelch ideas even if they are highly "virulent." So what can we do about how susceptible we are to conspiracy theories? It may take a generation, but I think we should focus on improving critical thinking skills in young people—kindergarten through college. We need to teach them to assess information analytically, to appreciate complexity, and to employ strategies against bias to mitigate the human tendency to seek simple answers and assign blame.

Rich Davis *Renton, Wash.*

"What can we do about how susceptible we are to conspiracy theories? I think we should focus on improving critical thinking skills in young people."

Rich Davis *Renton, Wash.*

I was surprised by the absence of a social psychologist among the breadth of disciplines represented in Quattrociocchi's own research group, although at least one was cited elsewhere. The results he described are consistent with social psychology research and theory dating back to the 1950s, and I would suggest that he add someone in that discipline to his team.

The echo chamber idea follows from social comparison theory (proposed by Leon Festinger in 1954), which tells us that when people want to learn the "truth" about issues, they look to others with whom they identify, typically those with like-minded beliefs and attitudes. The finding that debunking information actually increased conspiracy news consumption is exactly what cognitive dissonance theory (also proposed by Festinger, in 1957) would predict. When people perform an action consistent with their beliefs and are then confronted with information contradicting the implications of that action, they often resolve the contradiction by increasing the performance of the previous action.

Charles Pavitt *Department of Communication, University of Delaware*

TRIAL JUDGMENT

In "A Rare Success against Alzheimer's," Miia Kivipelto and Krister Håkansson describe a clinical trial on improving cognition in subjects aged 60 to 77 that they are involved in. The 631 individuals in the treatment group were directed to follow a regimen of a particular diet, including a vitamin D supplement, exercise and cognitive training, and the control group received health advice. Both groups were followed for cardiovascular health. The treatment group showed significant improvement during the two years of the investigation, and the control group also showed improvement, to a lesser degree.

There is no way to know which of the measures produced the observed effect. For a scientific study, one would expect the outcome to have been compared with groups receiving only one of each intervention. Moreover, although the authors describe selecting subjects with a high possibility of developing dementia and report that those with a gene variant linked to Alzheimer's risk "seemed to receive somewhat more benefit," the study did not involve any individuals who had the disease. It is disappointing that it thus did not truly address the possible effect these interventions might have on Alzheimer's. Obviously this is not possible with such a short study period, and it is comforting that the participants are now being followed for an additional seven years.

Jens Christian Jensenius *Professor emeritus, Department of Biomedicine, Aarhus University, Denmark*

I have co-authored two *Scientific American* articles in the past, and I find that Kivipelto and Håkansson's study falls short of being "a gold-standard clinical trial," as they state in their article. The authors' failure to cite the amounts of variance explained by each of their variables, independently or in conjunction with other variables, makes their conclusions equivocal. At best, their data confirm validity for a limited number of factors previously found in association with Alzheimer's but do not show that these are either primary causal factors or that they contribute to the disease with known amounts of impact (that is, the association may be purely incidental).

Further, with the gold-standard label of authenticity and the prestige of being a *Scientific American* cover story, this article could disturbingly imply that those suffering with this debilitating disease are, in some way, responsible for their condition—that had they maintained the specified diet, exercise routine, and so on, Alzheimer's could have been avoided. The risk of causal attribution may be said to exist in any research on factors associated with a medical condition, but avoiding it

is of particular importance here because of the terrible burden on caretakers.

NATHAN S. CAPLAN *Emeritus professor of psychology and emeritus research scientist, University of Michigan*

ON THE RECORD

As a physician, I find that "A Better Reckoning" [Science Agenda]—the editors' opinion piece on improving death certificates in the U.S.—fails to address two important issues. First, what is the actual cause of death? The editors note inaccuracies such as recording lung cancer when a patient had ovarian cancer metastasized in the lung. But say my patient is admitted to the hospital with a pulmonary embolism and dies. Was the culprit the hypotension caused by the embolism? Or the thrombophlebitis that led to the embolism? Or the hypercoagulable state that led to the thrombophlebitis?

Second, how do you code a death when you don't actually know the cause? For example, my patient, who was obese, diabetic and hypertensive and had coronary artery disease, is found dead. The family declines an autopsy, and the coroner refuses to do one because nothing suggests foul play. I am required to record a cause of death. Should I say heart attack, respiratory failure or possibly pulmonary embolism?

Having more detailed death certificates is clearly needed, but we also have to address the issues of the lack of clarity in how, exactly, we should indicate causation and our inability to assign a specific cause when many are possible and there is insufficient evidence to choose among them.

ED COLLOFF *via e-mail*

ERRATA

"Quick Hits," by Andrea Marks [Advances], reported that children younger than five have been nearly wiped out by malnutrition in Nigeria. It should have specified that this has occurred in Nigeria's state of Borno.

"Is there a link between music and math?" which appeared in Ask the Brains in the May/June 2017 issue of *Scientific American Mind,* has been updated online because of errors in the editing process. The revised version can be found at www.ScientificAmerican.com/article/is-there-a-link-between-music-and-math

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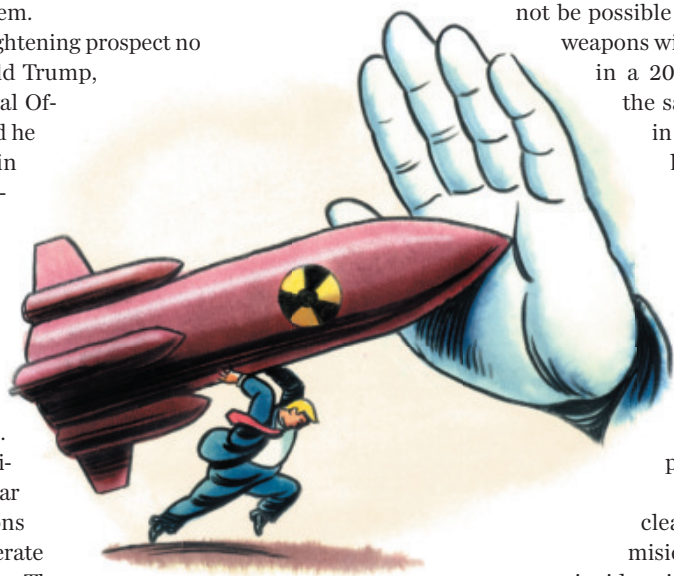
Nuclear War Should Require a Second Opinion

Leaving the decision to strike to the president alone is dangerous

By the Editors

In just five minutes an American president could put all of humanity in jeopardy. Most nuclear security experts believe that's how long it would take for as many as 400 land-based nuclear weapons in the U.S. arsenal to be loosed on enemy targets after an initial "go" order. Ten minutes later a battalion of underwater nukes could join them.

That unbridled power is a frightening prospect no matter who is president. Donald Trump, the current occupant of the Oval Office, highlights this point. He said he aspires to be "unpredictable" in how he might use nuclear weapons. There is no way to recall these missiles when they have launched, and there is no self-destruct switch. The act would likely set off a lethal cascade of retaliatory attacks, which is why strategists call this scenario mutually assured destruction.



With the exception of the president, every link in the U.S. nuclear decision chain has protections against poor judgments, deliberate misuse or accidental deployment. The "two-person rule," in place since World War II, requires that the actual order to launch be sent to two separate people. Each one has to decode and authenticate the message before taking action. In addition, anyone with nuclear weapons duties, in any branch of service, must routinely pass a Pentagon-mandated evaluation called the Personnel Reliability Program—a battery of tests that assess several areas, including mental fitness, financial history, and physical and emotional well-being.

There is no comparable restraint on the president. He or she can decide to trigger a thermonuclear Armageddon without consulting anyone at all and never has to demonstrate mental fitness. This must change. We need to ensure at least some deliberation before the chief executive can act. And there are ways to do this without weakening our military responses or national security.

This is not just a reaction to current politics. Calls for a bulwark against unilateral action go back more than 30 years. During the Reagan administration, the late Jeremy Stone, then president of the Federation of American Scientists, proposed that the president should not be able to order a first nuclear strike without consulting with high-ranking members of Congress. Such a buffer would ensure that actions that could escalate into world-destroying counterattacks would not be taken lightly. Democratic legislators recently introduced a law that would require not just consultation but congressional support for a preemptive nuclear attack. Whether or not that seems like the best check on presidential nuclear power is a matter for Congress.

We already know that second-check plans would not compromise American safety. Security experts used to worry that a hair-trigger launch was needed to deter a first strike by an enemy: our instant reactions would ensure that our opponent would feel catastrophic consequences of aggression. In the modern world, that is no longer the case. The U.S. has enough nukes in enough locations—including, crucially, our roving, nuclear-armed submarines—that nuclear strategists now agree it would not be possible to take out all of the nation's weapons with a first strike. The Pentagon, in a 2012 security assessment, said the same thing. It noted that even in the unlikely event that Russia launched a preemptive attack on the U.S.—and had more nuclear capability than current international agreements allow for—it "would have little to no effect on the U.S. assured second-strike capabilities." That conclusion suggests that we will have ample firepower even if two or more people discuss how to use it.

We have come close to nuclear war in the past because of misidentified threats, including an incident in 1979 in which computers at a military command center in Colorado Springs wrongly reported the start of a major Soviet nuclear offensive. Ballistic and nuclear bomber crews immediately sprang into action. Crisis was averted only after satellite data could not corroborate the warning, and American forces finally stood down. In our March issue, Scientific American called for taking the U.S. nuclear arsenal off high alert because of this and other such near misses.

Taking the arsenal off high alert is an important step. But putting another check into the system—removing one person's unfettered ability to destroy the world—will create another essential, lasting safeguard for the U.S. and the planet. SA

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Illustration by Ross MacDonald

The Right to Cognitive Liberty

A new type of brain-imaging technology could expose—even change—our private thoughts

By Marcello Ienca

The idea of the human mind as the domain of absolute protection from external intrusion has persisted for centuries. Today, however, this presumption might no longer hold. Sophisticated neuroimaging machines and brain-computer interfaces detect the electrical activity of neurons, enabling us to decode and even alter the nervous system signals that accompany mental processes. Whereas these advances have a great potential for research and medicine, they pose a fundamental ethical, legal and social challenge: determining whether or under what conditions it is legitimate to gain access to or interfere with another person's neural activity.

This question has special social relevance because many neurotechnologies have moved away from a medical setting and into the commercial domain. Attempts to decode mental information via imaging are also occurring in court cases, sometimes in a scientifically questionable way. For example, in 2008 a woman in India was convicted of murder and sentenced to life imprisonment on the basis of a brain scan showing, according to the judge, "experiential knowledge" about the crime. The potential use of neural technology as a lie detector for interrogation purposes has garnered particular attention. In spite of experts' skepticism, commercial companies are marketing the use of functional MRI- and electroencephalography-based technology to ascertain truth and falsehood. The military is also testing monitoring techniques for another reason: to use brain stimulation to increase a fighter's alertness and attention.

Brain-reading technology can be seen as just another unavoidable trend that erodes a bit more of our personal space in the digital world. But given the sanctity of our mental privacy, we might not be so willing to accept this intrusion. People could, in fact, look at this technology as something that requires the reconceptualization of basic human rights and even the creation of neurospecific rights.

Lawyers are already talking about a right to cognitive liberty. It would entitle people to make free and competent decisions regarding the use of technology that can affect their thoughts. A right to mental privacy would protect individuals against unconsented-to intrusion by third parties into their brain data, as well as against the unauthorized collection of those data. Breaches of privacy at the neural level could be more dangerous than conventional ones because they can bypass the level of conscious reasoning, leaving us without protections from having our mind read involuntarily. This risk applies not only to predatory marketing studies or to courts using such technology excessively but also to applications that would affect general consumers. This last category is growing. Recently Facebook unveiled a plan to create a speech-to-text interface to translate thoughts directly from brain to computer. Similar attempts are being made by companies such as Samsung and Netflix. In the future, brain control could replace the keyboard and speech recognition as the primary way to interact with computers.

If brain-scanning tools become ubiquitous, novel possibilities for misuse will arise—cybersecurity breaches included. Medical devices connected to the brain are vulnerable to sabotage, and neuroscientists at the University of Oxford suggest that the same vulnerability applies to brain implants, leading to the possibility of a phenomenon called brainjacking. Such potential for misuse might prompt us to reconceptualize the right to mental integrity, already recognized as a fundamental human right to mental health. This new understanding would not only protect people from being denied access to treatment for mental illness but would also protect all of us from harmful manipulations of our neural activity through the misuse of technology.

Finally, a right to psychological continuity might preserve people's mental life from external alteration by third parties. The same kind of brain interventions being explored to reduce the need for sleep in the military could be adapted to make soldiers more belligerent or fearless. Neurotechnology brings benefits, but to minimize unintended risks, we need an open debate involving neuroscientists, legal experts, ethicists and general citizens. SA

Marcello Ienca is a Ph.D. candidate at the Institute for Biomedical Ethics at the University of Basel and is chair of the Student/Postdoctoral Committee at the International Neuroethics Society.

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Illustration by Christian Dellavedova

ADVANCES

The primate brain has an uncanny ability to recognize faces. Now researchers are starting to crack that code.

GETTY IMAGES

INSIDE

NEUROSCIENCE

Saving Face

Scientists are closing in on the neural code for facial recognition

The brain has evolved to recognize and remember many different faces. We can instantly identify a friend's countenance among dozens in a crowded restaurant or on a busy street. And a brief glance tells us whether that person is excited or angry, happy or sad.

Brain-imaging studies have revealed that several blueberry-size regions in the temporal lobe—the area under the temple—specialize in responding to faces. Neuroscientists call these areas "face patches." But neither brain scans nor clinical studies of patients with implanted electrodes explained exactly how the cells in these patches work.

Now, using a combination of brain imaging and single-neuron recording in macaques, biologist Doris Tsao and her colleagues at the California Institute of Technology appear to have finally cracked the neural code for primate face recognition. The researchers found the firing rate of each face patch cell corresponds to a separate facial feature. Like a set of dials, the cells can be fine-tuned to respond to bits of information, which they can then combine in various ways to create an image of every face the animal encounters. "This was mind-blowing," Tsao says. "The values of each dial are so predictable that we can re-create the face that a monkey sees by simply tracking the electrical activity of its face cells."

Previous studies had hinted at the specificity of these brain areas for encoding faces.

The original face (*1*) presented to a monkey and the face predicted by its brain activity (*2*).

In the early 2000s, when Tsao was a postdoctoral researcher at Harvard Medical School, she and electrophysiologist Winrich Freiwald showed that neurons in a monkey's face patches would fire electrical signals every time the animal saw pictures of a face. But the same brain cells showed little or no response to other objects, such as images of vegetables, radios or nonfacial body parts. Other experiments indicated that neurons in these regions could also distinguish among individual faces, even if they were cartoons.

In a famous set of experiments in human subjects in 2005, neuroscientist Rodrigo Quian Quiroga found that pictures of actor Jennifer Aniston activated a single brain cell in the hippocampus region—the so-called Jennifer Aniston neuron. A similar process was thought to occur elsewhere in the temporal lobe, where the prevailing theory held that each neuron in the face patches was sensitive to a few particular people, says Quian Quiroga, who is now at the University of Leicester in England and was not involved with the current work. But Tsao's recent study suggests that theory may be mistaken. "She has shown that neurons in face patches don't encode particular people at all; they just encode certain features," Quian Quiroga says. "That completely changes our understanding of how we recognize faces."

To decipher how cells perform this recognition task, Tsao and postdoc Steven Le Chang generated 2,000 human mug shots with variations in 50 features, including facial roundness, distance between the eyes, and skin tone and texture. They showed these images to two monkeys while recording electrical activity from individual neurons in three separate face patches in both animals.

Each neuron responded to only a single feature, the researchers found. Rather than encoding individuals' faces, like the Jennifer Aniston neuron in the hippocampus, the face patch neurons were dividing images into smaller regions and encoding specific features such as hairline width, Chang says. Moreover, the neurons in separate face patches processed complementary information. Like factory workers, the various face patches had distinct jobs, cooperating, communicating and building on one another to provide a complete picture.

Once Chang and Tsao knew how this division of labor occurred, they could predict the neurons' responses to a completely novel face. They developed a mathematical model in which facial features were encoded by various neurons. Then they showed monkeys a previously unseen image of a human face (*1*). Using their algorithm for how various neurons would respond, the researchers were able to digitally re-create the visage that a monkey had viewed (*2*). "The re-creations were stunningly accurate," Tsao says. In fact, they were nearly indistinguishable from the actual pictures the monkeys saw.

Even more surprisingly, the researchers needed readings from only a relatively small set of neurons for the algorithm to accurately re-create the faces monkeys were seeing, Tsao says. Recordings from just 205 cells—106 in one patch and 99 in another—were enough. "It really speaks to how compact and efficient this feature-based neural code is," she says. It may also explain why primates are so good at facial recognition and how we can potentially distinguish among billions of different people without needing an equally massive number of face cells.

The findings, which were published recently in *Cell*, provide scientists with a comprehensive, systematic model for how the brain perceives faces. This human cerebral machinery is very similar to that of monkeys, and we have face patches that respond like theirs to images in functional MRI studies, according to researchers. Yet the number of human face patches might differ.

Understanding the brain's facial code could help scientists study how face cells incorporate other identifying information, such as sex, age, race, emotional cues and names, says Adrian Nestor, a neuroscientist at the University of Toronto who studies face patches in human subjects and did not participate in the research. It may even provide a framework for decoding how the brain processes nonfacial shapes. "Ultimately, this puzzle is not just about faces," he explains. "The hope is that this neural code extends to object recognition as a whole." —*Knvul Sheikh*

COURTESY OF STEVEN LE CHANG *California Institute of Technology*

ECOLOGY

Aussie Invaders

The land down under launches its latest effort to eradicate an unwelcome species

The Australian government unleashed a strain of a hemorrhagic disease virus into the wild earlier this year, hoping to curb the growth of the continent's rabbit population. This move might sound barbaric, but the government estimates that the animals—brought by British colonizers in the late 18th century—gnaw through about $115 million in crops every year. And the rabbits are not the only problem. For more than a century Australians have battled waves of invasive species with many desperate measures—including introducing nonnative predators—to limited avail.

Australia is not the only country with invasive creatures. But because it is an isolated continent, most of its wildlife is endemic—and its top predators are long extinct. This gives alien species a greater opportunity to thrive. "In other places, you'll see a much bigger predator community," says Euan Ritchie, one of the directors of the Ecological Society of Australia. But the Tasmanian tiger, the marsupial lion and *Megalania* (a 1,300-pound lizard) are gone. The only top predator left, the Australian wild dog, or dingo (*photograph*), is under threat from humans because of its predilection for eating sheep.

Along with rabbits, Australia is trying to fend off red foxes (imported for hunting), feral cats (once kept as pets), carp (brought in for fish farms) and even camels (used for traversing the desert). Wildlife officials have attempted to fight these invaders by releasing viruses, spreading poisons, building thousands of miles of fences, and sometimes hunting from helicopters. In one famous case, the attempted solution became its own problem: the cane toad was introduced in 1935 to prey on beetles that devour sugarcane. But the toads could not climb cane plants to reach the insects and are now a thriving pest species themselves.

Despite scientists' protestations, the government plans to introduce another virus later this year to try reducing the out-of-control carp population. "We can't go back to the past," Ritchie says. But "we have a lot of native mammals and other species that are holding on." —*Erin Biba*

GETTY IMAGES

CONSERVATION

Find My Elephant

Cutting-edge tech may give conservationists the upper hand over poachers

There's an app for that: new high-tech tracking collars could help avert poaching.

MIKE HILL *Getty Images*

How does one protect elephants from poachers in an African reserve the size of a small country? This daunting task typically falls to park rangers who may spend weeks patrolling the bush on foot, sometimes lacking basic gear such as radios, tents or even socks. They are largely losing to ivory poachers, as attested by the latest available data on Africa's two species of elephant, both threatened: savanna elephant populations fell 30 percent between 2007 and 2014, and those of forest elephants plummeted by 62 percent between 2002 and 2011.

To stem the losses, conservationists are increasingly turning to technology. The latest tool in the arsenal: real-time tracking collars, developed by the Kenya-based nonprofit Save the Elephants and currently being used on more than 325 animals in 10 countries. The organization's researchers wrote algorithms that use signals from the collars to automatically detect when an animal stops moving (indicating it may be dead), slows down (suggesting it may be injured) or heads toward a danger zone, such as an area known for rampant poaching. Experimental accelerometers embedded in the collars detect aberrant behaviors such as "streaking"—sudden, panicked flight that might signal an attack. Unlike traditional tracking collars, many of which send geographical coordinates infrequently or store them onboard for later retrieval, these devices' real-time feeds enable rangers to react quickly. In several cases, they have led to arrests.

The amount of data produced by the new collars quickly became overwhelming, however. So Save the Elephants partnered with Vulcan—a company created by Microsoft co-founder Paul Allen—which engineered an open-source tracking application for iOS and the Web called the Domain Awareness System. The DAS app sends alerts when a potential problem arises—if an elephant bolts, for example, or if field sensors pick up on human intruders. It also integrates a wealth of other information, including the positions of nearby rangers, vehicles and aircraft, as well as detected gunshots, camera trap feeds, arrest and crime-scene records, weather, and more.

Some of the technologies used in the collars—GPS, onboard data storage, phone or satellite receivers—are found in everyday devices, including smartphones. Yet in this case these tools are being applied in an exceptional way, according to Jake Wall, geospatial science adviser for Save the Elephants. It is the first time all the data that DAS uses have been presented in one neat feed and map, he says.

An early version of the program is being tested at four sites in Africa, with a 10-site expansion planned for September. At Lewa Wildlife Conservancy in Kenya, DAS is already seen as a game changer after its launch less than a year ago, says Batian Craig, director of 51 Degrees, a private company that oversees security operations at Lewa: "Being able to visualize all this information in one place and in real time makes a massive difference to protected-area managers."

—*Rachel Nuwer*

ENERGY

Emission Permission

Mexico's stock market pilots a program to buy and sell the right to pollute

1

2

In January protesters in Mexico took to the streets to express their anger at the gasoline price hike, or *gasolinazo* (*1*). Demonstrators set fire to a truck in Mexico City in protest of a price hike in 2009 (*2*).

Mexico kicked off 2017 with a 20 percent spike in gasoline prices, driven in part by the phasing out of subsidies. Some consumers set fires at gas stations—a response that highlights the backlash countries can face as they stop subsidizing carbon-based fuels and start encouraging climate-friendly alternatives. Now the Mexican government and stock market are experimenting with a gentler tool for discouraging carbon emissions: cap-and-trade. Mexico, which in 2012 passed the developing world's first climate law, is well placed to set an example for other developing economies looking to shrink their carbon footprints.

In cap-and-trade programs, regulators issue permits allowing companies to pollute a certain amount. In most systems, the cap gets lower over time, giving businesses a choice: slash emissions further or buy permits on the market from another company.

More than 80 Mexican companies are signed up to simulate permit trading. Using software developed by an organization within the Mexican Stock Exchange—MÉXICO2—companies are familiarizing themselves with the everyday logistics of carbon trading, says MÉXICO2 research analyst Andrés Prieto. By late 2018 the federal government will require Mexico's biggest emitters to participate.

The nation has a cooperation agreement with California, which already trades carbon permits with several Canadian provinces. For now Mexico is learning from its North American neighbors' experience and may eventually join that market. "The very big lesson we learned in California, in comparison with Europe, is that it is not enough to have certainty about the emissions quantity," Prieto says. Polluters also want a forecast for permit prices. In Europe's market, price volatility discouraged companies from making long-term investments in reducing their environmental footprint, despite a steadily lowering carbon cap. Mexico may also require a minimum price for carbon emission permits, as California does, so companies can better predict their future financial positions.

Mexico has no shortage of polluting industries—so progress in cutting emissions is within reach if the country can build up the capacity to regulate them, says economist Juan-Carlos Altamirano of the World Resources Institute in Washington, D.C.

—Lucas Laursen

ALFREDO ESTRELLA *Getty Images (protest)*; DAVID DE LA PAZ *Redux Pictures (burning truck)*

IN THE NEWS

Quick Hits

SWITZERLAND

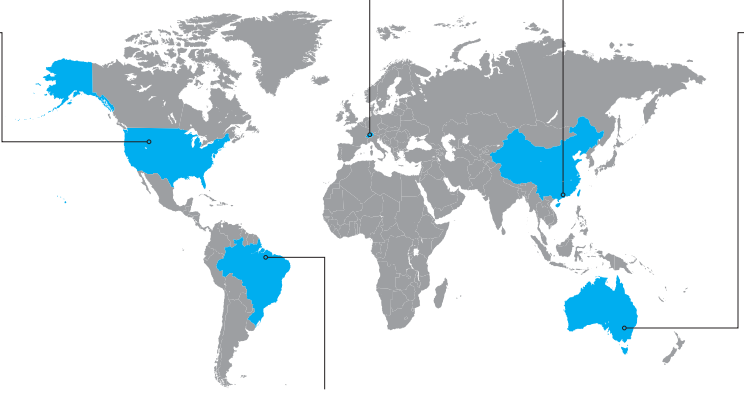
Researchers and composers are collaborating to translate data from CERN's Large Hadron Collider near Geneva, the world's biggest particle accelerator, into music. The joint effort by Plymouth University in England, the Massachusetts Institute of Technology and CERN aims to organize the resulting tunes into a composition to be played by a pianist from the Juilliard School in the spring of 2018.

CHINA

African park rangers who protect elephants gathered in Hong Kong to insist that the region ban all ivory sales and confiscate stockpiled supplies without reimbursing vendors. Local officials said they welcomed the rangers' input as part of their ongoing effort to eliminate Hong Kong's ivory trade by 2021.

U.S.

The National Academies of Sciences, Engineering, and Medicine identified elk as the primary source of a bacterial infection that has been plaguing cattle in the Greater Yellowstone Area. The disease, caused by *Brucella* bacteria, has been raging there for two decades—so targeting elk transmission might squash the outbreak for good.



AUSTRALIA

In the past three decades water bird population numbers have dropped by 70 percent around Australia's most heavily developed river basin, the Murray-Darling, a study finds. The researchers, from the University of New South Wales, pin the decline on dam construction and wetland drainage.

BRAZIL

The world's oldest mushroom fossil was discovered in northeastern Brazil, pushing back gilled mushrooms' origin to between 120 million and 113 million years ago. The next oldest specimen is 99 million years old.

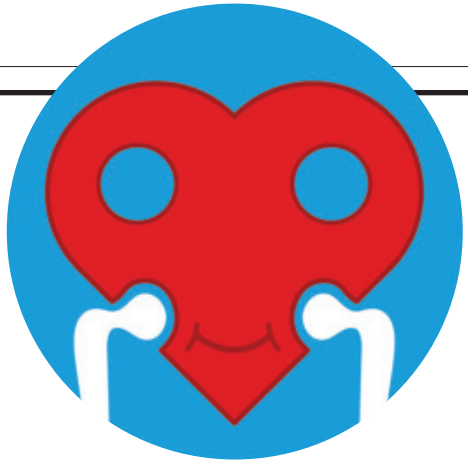
—Leslie Nemo

For more details, visit
www.ScientificAmerican.com/aug2017/advances

HEALTH

Mending a Broken Heart

An injectable, stem cell–based therapy for heart failure is getting a gold-standard trial



In the days after a heart attack, surviving patients and their loved ones can breathe a sigh of relief that the immediate danger is over—but the scar tissue that forms during the long healing process can inflict lasting damage. Too often it restricts the heart's ability to fill properly between beats, disrupting rhythm and ultimately leading to heart failure. Yet a new possible treatment may help to revitalize an injured ticker.

A cadre of scientists and companies is now trying to prevent or reverse cardiac damage by infusing a cocktail of stem cells into weakened hearts. One company, Melbourne, Australia–based Mesoblast, is already in late-stage clinical trials, treating hundreds of chronic heart failure patients with stem cell precursors drawn from healthy donors' hip bones. A randomized trial that includes a placebo group is scheduled to complete enrollment next year.

Mesoblast's earlier-stage trials, published in 2015 in *Circulation Research,* found that patients who received injections of its cell mixture had no further problems related to heart failure.

Promising results from the new trial would be a major step forward for a field that has long been criticized for studies that are poorly designed, incomplete or lack control-group comparisons, as well as for the peddling of unproved therapies in many clinics worldwide.

Another company, Belgium-based TiGenix, hopes to attack scar tissue before it forms by treating patients with a mixture of heart stem cells within seven days of a heart attack. This approach has just completed phase II trials, but no findings have yet been published.

There are still many unanswered questions about how stem cells—typically derived from bones—could help heal the heart. Leading theories suggest they may help fight inflammation, revitalize existing heart cells, or drive those cells to divide or promote new blood-vessel growth, says Richard Lee, leader of the cardiovascular program at the Harvard Stem Cell Institute. Other stem cell scientists, including Joshua Hare, who conducted earlier-stage Mesoblast research and directs the Interdisciplinary Stem Cell Institute at the University of Miami, say the cells may work in multiple ways to heal scar tissue. According to Hare, the stem cells could ultimately be a "truly regenerative treatment." —*Dina Fine Maron*

Illustration by Thomas Fuchs

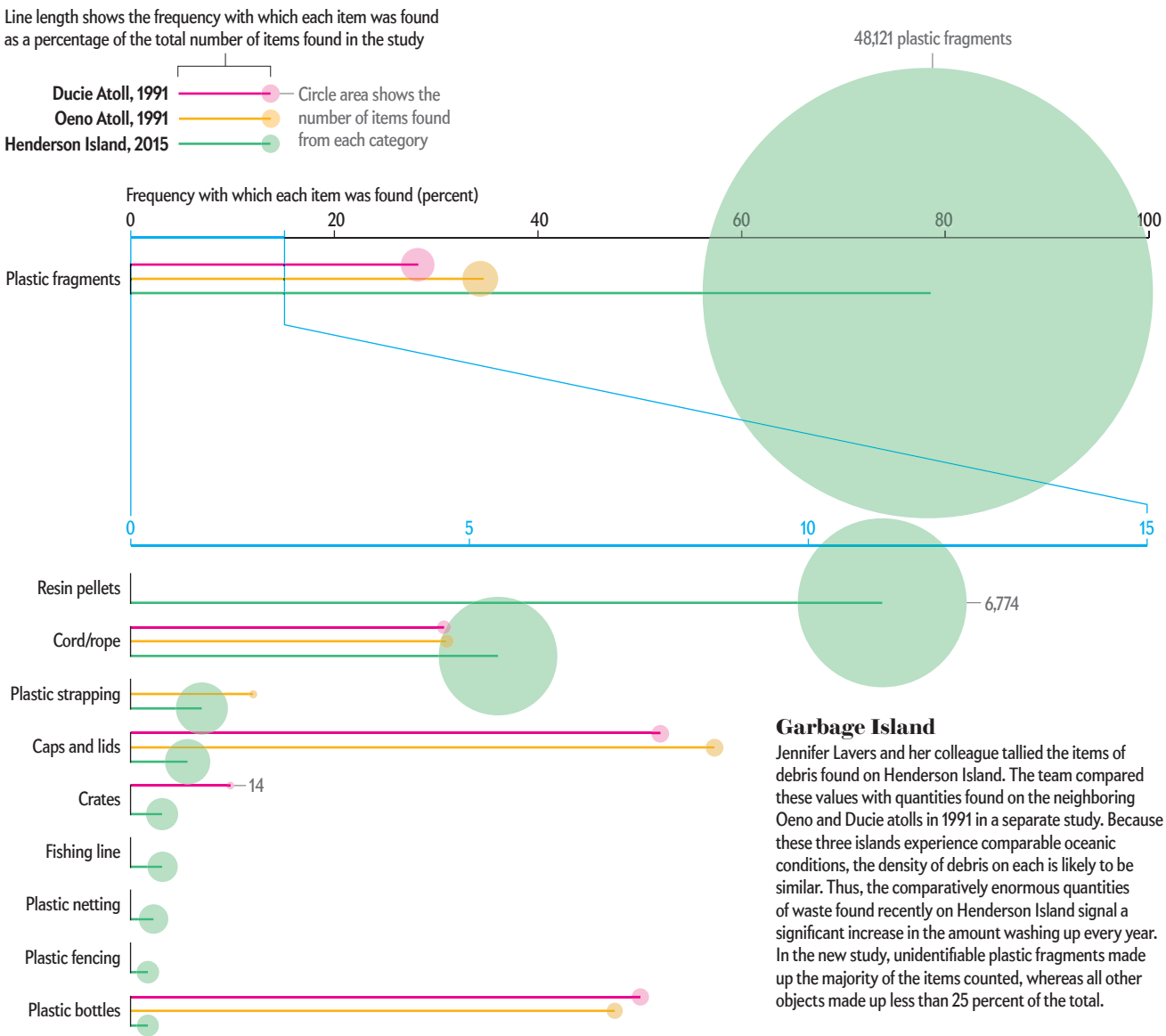
ENVIRONMENT

Awash in Plastic

An uninhabited island is covered in about 18 metric tons of trash

Henderson Island, a tiny, unpopulated coral atoll in the South Pacific, could scarcely be more remote. The nearest city of any size lies some 5,000 kilometers away. Yet when Jennifer Lavers, a marine biologist at the Institute for Marine and Antarctic Studies in Tasmania, ventured there two years ago to study invasive rodent-eradication efforts, she found the once pristine UNESCO World Heritage Site inundated with trash—17.6 metric tons of it, she conservatively estimates—pretty much all of it plastic. (The rubbish originates elsewhere but hitches a ride to Henderson on wind or ocean currents.) One particularly spoiled stretch of beach yielded 672 visible pieces of debris per square meter, plus an additional 4,497 items per square meter buried in the sand, Lavers and her colleague reported recently in the *Proceedings of the National Academy of Sciences USA*.

By comparing the data with a study of the nearby Ducie and Oeno atolls conducted in 1991, the team extrapolated that there is between 200 and 2,000 times more trash on Henderson now than there was on those neighboring islands back then. Unidentifiable plastic fragments, resin pellets and fishing gear make up the bulk of the total (*graphic*), but the researchers also came across toothbrushes, baby pacifiers, hard hats, bicycle pedals and a sex toy. Thousands of new items wash up daily and make any cleanup attempt impractical, according to Lavers, who specializes in studying plastic pollution. Meanwhile many of the world's other coastlines could face a similar threat. "Regardless of where I go or how far removed from society," Lavers says, "plastic is what I find." —*Jesse Greenspan*



Garbage Island

Jennifer Lavers and her colleague tallied the items of debris found on Henderson Island. The team compared these values with quantities found on the neighboring Oeno and Ducie atolls in 1991 in a separate study. Because these three islands experience comparable oceanic conditions, the density of debris on each is likely to be similar. Thus, the comparatively enormous quantities of waste found recently on Henderson Island signal a significant increase in the amount washing up every year. In the new study, unidentifiable plastic fragments made up the majority of the items counted, whereas all other objects made up less than 25 percent of the total.

SOURCE: "EXCEPTIONAL AND RAPID ACCUMULATION OF ANTHROPOGENIC DEBRIS ON ONE OF THE WORLD'S MOST REMOTE AND PRISTINE ISLANDS," BY JENNIFER L. LAVERS AND ALEXANDER L. BOND, IN *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES USA*, VOL. 114, NO. 23; JUNE 6, 2017

Graphic by Amanda Montañez

Wax worms, such as the one shown here, can gnaw through and break down plastic.

BIOCHEMISTRY

Plastic-Eating Worms

Larvae that consume and degrade polyethylene could inspire new industrial tools

Humans produce more than 300 million metric tons of plastic every year. Almost half of that winds up in landfills, and up to 12 million metric tons pollute the oceans. So far there is no sustainable way to get rid of it, but a new study suggests an answer may lie in the stomachs of some hungry worms.

Researchers in Spain and England recently found that the larvae of the greater wax moth can efficiently degrade polyethylene, which accounts for 40 percent of plastics. The team left 100 wax worms on a commercial polyethylene shopping bag for 12 hours, and the worms consumed and degraded about 92 milligrams, or roughly 3 percent, of it. To confirm that the larvae's chewing alone was not responsible for the polyethylene breakdown, the researchers ground some grubs into a paste and applied it to plastic films. Fourteen hours later the films had lost 13 percent of their mass—presumably broken down by enzymes from the worms' stomachs.

When inspecting the degraded plastic films, the team also found traces of ethylene glycol, a product of polyethylene breakdown, signaling true biodegradation. Their findings were published earlier this year in *Current Biology*.

Study co-author Federica Bertocchini, a biologist at Spain's Institute of Biomedicine & Biotechnology of Cantabria, says the larvae's ability to break down their dietary staple—beeswax—also allows them to degrade plastic. "Wax is a complex mixture of molecules, but the basic bond in polyethylene, the carbon-carbon bond, is there as well," she explains. "The wax worm evolved a mechanism to break this bond."

Jennifer DeBruyn, a microbiologist at the University of Tennessee, who was not involved in the study, says it is not surprising that an organism evolved the capacity to degrade polyethylene. But compared with previous studies, she finds the speed of biodegradation in this one exciting. The next step, DeBruyn says, will be to pinpoint the cause of the breakdown. Is it an enzyme produced by the worm itself or by its gut microbes? Bertocchini agrees and hopes her team's findings might one day help harness the enzyme to break down plastics in landfills, as well as those scattered throughout the ocean. But she envisions using the chemical in some kind of industrial process—not simply "millions of worms thrown on top of the plastic."

—Matthew Sedacca

FEDERICA BERTOCCHINI, PAOLO BOMBELLI AND CHRIS HOWE

Hundreds of millions of years ago massive volcanic eruptions may have triggered an ice age that kicked off Earth's first mass extinction, wiping out most of the world's marine species.

SEBASTIAN CRESPO *Getty Images (lava)*; ULET IFANSASTI *Getty Images (smoke)*

GEOLOGY

Fire and Ice

Volcanoes are now thought to have triggered all five major mass extinctions

Roughly 450 million years ago a region that was likely the size of Europe started to stretch and tear. Deep gashes opened in Earth's crust, spewing lava that leaped into the air in luminous walls that reached up to 500 meters. Although the ground eventually grew still, the damage had just begun. Once the lava hardened, rainwater dissolved carbon dioxide that the volcanoes had pumped into the atmosphere, washing it back into the ground. Removing the greenhouse gas caused glaciers to creep forward and sea levels to drop, plunging the planet into an ice age that wiped out 85 percent of all marine species.

Researchers laid out this fire-and-ice scenario in a paper recently published in *Geology*. If confirmed, the findings would offer the first solid clue as to what caused Earth's first mass extinction—hypothesized to be the result of everything from toxic metals unleashed in the oceans to radiation from a distant gamma-ray burst. It also places the so-called Late Ordovician mass extinction in good company: all four other such events have previously been tied to volcanic eruptions.

Lead study author David Jones, a geologist at Amherst College, did not expect this to be the case for the first mass extinction. He initially set out to further disprove the volcanic explanation. But when he "cooked" Late Ordovician rocks from Nevada and southern China in the laboratory, they released large amounts of mercury—a telltale sign that volcanoes had rocked our world.

Now the researchers hope to locate a large igneous province—a vast swath of hardened lava—that would date back to the time of the extinction. "It's like if you go to a crime scene and find a dead body with a bullet hole in it. The next step is to look for the gun," says Seth Burgess, a U.S. Geological Survey geologist, who was not involved in the study. If they find it, he asserts, they will look to see whether "there are gunpowder marks on it."

Jones has already begun the detective work. Although he and his colleagues suspect the volcanoes sparked a global ice age, Burgess and others think the story is a little more complicated because volcanoes often have the effect of toasting the atmosphere instead of cooling it. Still, with all five mass extinctions linked to volcanic eruptions, geologists can start to tease out the details of each murder mystery. —*Shannon Hall*

The Computer Will See You Now

Sophisticated software could help doctors make better diagnoses

By Dina Fine Maron

Recently a middle-aged patient visited Seattle-based physician Thomas Payne complaining about substantial, unexpected weight loss and foot tingling. The doctor was puzzled—those symptoms could indicate anything from an infection to dozens of more complex ailments, such as diabetes or cancer. So Payne, who also serves as medical director of information technology services at the University of Washington School of Medicine, did something unusual. After performing a standard physical examination and filling in his patient's medical record, he turned to an online tool—DXplain—for help.

Payne keyed in the symptoms, and the computer program suggested a handful of potential conditions, including a rare disease called amyloidosis, in which abnormal proteins build up in the body, interfering with normal organ function and causing nerve damage. Further exams and a biopsy at another institution confirmed the tip—the patient was one of the roughly 4,000 people in the U.S. who receive this diagnosis every year.

Even five years ago, if Payne had been stumped about a case, he would have first turned to a trusted colleague or spent hours sifting through a mountain of textbooks and scientific research to puzzle out such an obscure diagnosis. DXplain draws on those same textbooks and peer-reviewed studies to make its own assessments—but does so within seconds. "Could I have come up with that same list of conditions? Perhaps if I thought long enough," says Payne, who more typically sees patients with the flu or arthritis than with inexplicable nerve damage. But, he warns, the scientific literature shows that "when pressed for time, we don't sit down and think about these things like we should, and then those diagnoses may be missed."

Such misses are too common, according to the National Academies of Sciences, Engineering, and Medicine, which published major reports on the causes of medical errors in 1999 and 2015. Some of these errors can arise from poor record keeping or miscommunication. But often misdiagnosis is to blame. Reviews of medical transcripts suggest that between 6 and 17 percent of adverse events in hospitals can be tied to mistaken diagnoses. The National Academies' 2015 report estimated that 10 percent of patient deaths in the U.S. result from these incorrect conclusions—and the corresponding inappropriate treatment.

Among the solutions that the academies recommended was that hospitals and clinicians should employ more tools—formally referred to as clinical decision-support systems—that might help improve their decision making. At its most basic level, that could mean following a checklist to avoid skipping key steps in important routines. A growing number of medical schools, teaching hospitals and other care centers are also paying for computer-based assistance such as DXplain or its competitors VisualDx and Isabel. Right now VisualDx, the most popular diagnostic support system, is licensed at more than 1,600 hospitals and clinics across the U.S., according to its manufacturer.

The clinical decision-support industry says its wares can help clinicians confirm their diagnoses or suggest alternatives. But physicians have not exactly embraced the new tools with open arms. The big question is whether adopting such software

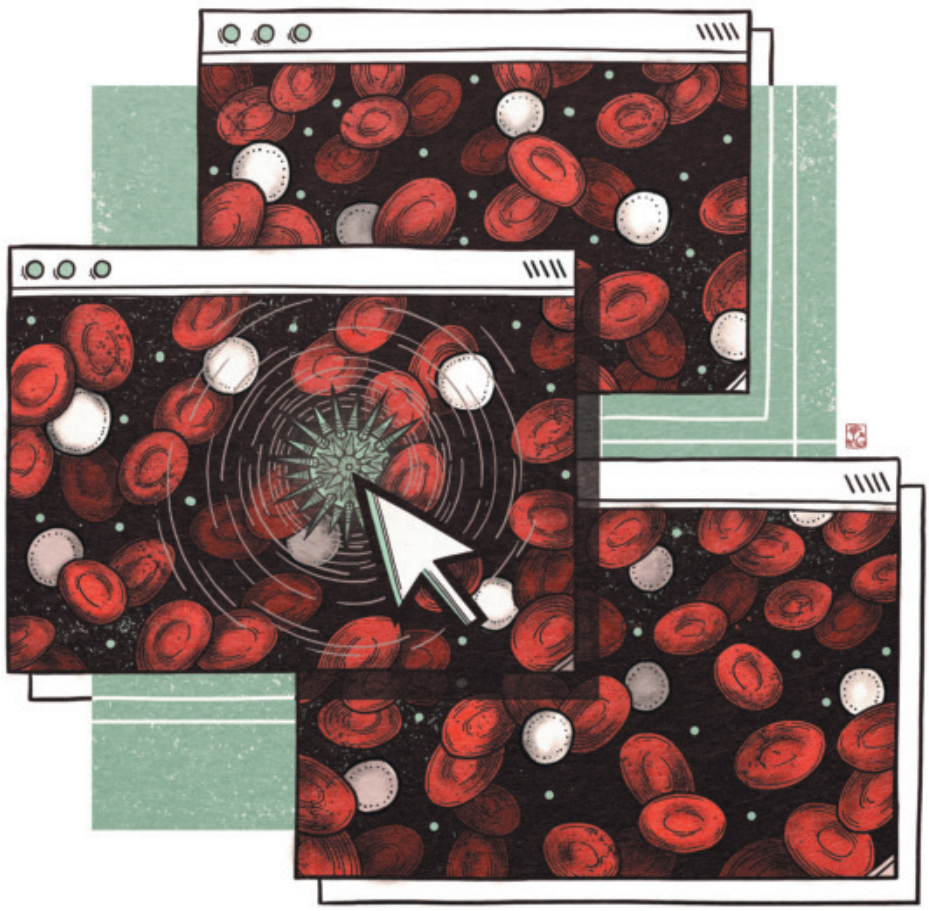


Illustration by Christina Chung

Dina Fine Maron is associate editor for biology and medicine at *Scientific American*.

solutions will substantially enhance the practice of medicine or simply add another unnecessary complication to doctors' already pressed schedules.

PROCESSING POWER

THE IDEA OF ENLISTING COMPUTERS to help inform medical diagnoses is not new. The first computing efforts that targeted clinicians' errors began in the 1970s. Then, in the mid-1980s, Massachusetts General Hospital began working on DXplain with the goal of helping to improve diagnoses. The approach seemed promising, but it did not actually take off at the time, partly because patient records were still being written by hand, and turning to a computer-based program added another cumbersome step.

A lot has happened since then. Computers are now integral to standard medicine. They have taken over record keeping in most clinics, hospitals and private practices, with encouragement from federal incentives. Such shifts have boosted quality, safety and efficiency in the health care system.

The clinical decision-support systems have changed, too. They have become much faster and often link directly to the studies from which they draw, allowing clinicians to quickly assess evidence and learn more about the potential diagnosis. VisualDx, for that matter, highlights its "visual" aspect—it includes diagrams of what body parts may be affected and pictures of maladies for easier comparison.

Crucially, scientists have also learned more about why people make certain kinds of mistakes and how to counteract them. Researchers have identified a number of cognitive traps into which physicians sometimes fall when making a diagnosis. One that seems particularly amenable to correction by computers is the so-called anchoring error. Studies suggest that doctors often get stuck on the first diagnosis that occurs to them—the anchor—even if it is wrong. Then they may subconsciously give greater weight to any information that reinforces that diagnosis and dismiss—or not even bother to look for—other data.

HUMAN ERROR

IN A BUSY HOSPITAL WARD or medical practice, anchoring errors can happen for myriad reasons. A harried clinician may forget to ask if a patient recently traveled even when that answer could substantially change the likely diagnosis—resulting in situations where, for example, an Ebola patient might be sent home from a hospital with instructions to take Tylenol for a high fever and pain rather than being quarantined and provided immediate care. Still other problems may stem from the way doctors are educated. Often students are given case studies that reflect prototypical symptoms rather than real-world complexities. Textbook cases are not as common as one might think.

That kind of discrepancy is where these systems hope to find their sweet spot. Each program employs proprietary algorithms to link symptoms with diagnoses and flag which conditions may be most likely or most dangerous and so need to be ruled out quickly. Some are even capable of automatically pulling information from a patient's current electronic records, thereby reducing the need for doctors to reenter the same information.

Just how much decision-support programs would slash errors, however, remains hard to estimate. But preliminary data look promising. A 2011 study of VisualDx compared how well emergency room doctors at two different institutions were able to diagnose a particular skin infection with and without computer assistance. Clinicians who used VisualDx made the correct diagnosis 64 percent of the time. Those who did not made the correct diagnosis only 14 percent of the time. A preliminary study of Isabel presented at a conference in 2014 concluded that the service improved the ability of 40 medical students to make accurate diagnoses by as much as a third. A study of DXplain, published in 2010, found that when residents at the Mayo Clinic used it with diagnostically complex cases, the program dramatically decreased medical costs because it led to shorter, more effective hospital stays.

HURDLES TO CLEAR

NEVERTHELESS, BENEFICIAL CHANGES are often slow in coming. In July the National Academies held a one-day meeting to check on progress in reducing diagnostic errors. John Ball, the physician who chaired the academies' 2015 report, said ahead of the meeting that he expected "disappointing" results because many of the recommendations to reduce error—including greater use of computerized decision-making tools—have not yet been adopted on a large scale. Ball says his own seven-hospital system in North Carolina has not yet made much progress integrating these systems into its care.

Part of the problem in North Carolina, Ball notes, is that the various hospitals and doctors in his network work with different electronic record-keeping systems and protocols, which makes it impossible to standardize such changes. The other issue, he says, is that doctors may be reluctant to spend time learning the system until they are certain that it will be worth it.

Institutional inertia is an issue across the U.S., observes Mark Graber, president and co-founder of the Society to Improve Diagnosis in Medicine. "Health care organizations don't really 'own' the problem of diagnostic error and don't recognize it as something they need to focus on," he says. "Physicians, in general, think they are doing a good job and think they don't really need to worry about [it]."

In addition, some experts, such as Sandra Fryhofer, a past president of the American College of Physicians and a practicing internist in Atlanta, fear that widespread adoption of these programs might have unintended consequences. If such software becomes more accessible to patients, she worries that they may forgo a doctor's visit because they think they already know what is wrong or, alternatively, needlessly fret because the program suggests a scary result—something that doctors say happens now when people search for their symptoms on the Internet.

Doctors such as Payne say they are not concerned about being replaced, however. What they envision is a safer, smarter approach—like the complex backup systems in a plane's cockpit. They hope that with such built-in redundancies and cues, perhaps they can chart a more reliable, smoother course for us all. SA

Technology as Magic

The products that really wow us seem like pure wizardry

By David Pogue

We the people have always been helplessly drawn to the concept of magic: the notion that you can will something to happen by wiggling your nose, speaking special words or waving your hands a certain way. We've spent billions of dollars for the opportunity to see what real magic might look like, in the form of *Harry Potter* movies, superhero films and TV shows, from *Bewitched* on down.

It should follow, then, that any time you can offer *real* magical powers for sale, the public will buy it. That's exactly what's been going on in consumer technology. Remember Arthur C. Clarke's most famous line? "Any sufficiently advanced technology is indistinguishable from magic." Well, I've got a corollary: "Any sufficiently magical *product* will be a ginormous hit."

Anything invisible and wireless, anything that we control with our hands or our voices, anything we can operate over impossible distances—those are the hits because they most resemble magic. You can now change your thermostat from thousands of miles away, ride in a car that drives itself, call up a show on your TV screen by speaking its name or type on your phone by speaking to it. Magic.

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

For decades the conventional wisdom in product design has been to "make it simpler to operate" and "make it easier for the consumer." And those are admirable goals, for sure. Some of the biggest technical advancements in the past 30 years—miniaturization, wireless, touch screens, artificial intelligence, robotics—have been dedicated to "simpler" and "easier."

But that's not enough to feel magical. Real tech magic is simplicity *plus awe*. The most compelling tech conventions—GPS apps telling you when to turn, your Amazon Echo answering questions for you, your phone letting you pay for something by waving it at that product—feel kind of amazing every single time.

The awe component is important. It's the difference between magic and mere convenience. You could say to your butler, "Jeeves, lock all the doors"—and yes, that'd be convenient. But saying, "Alexa, lock all the doors," and then hearing the deadbolts all over the house click *by themselves?* Same convenience, but this time it's magical.

Now, creating magic requires a lot of extra effort; to make something seem nontechnological, the designers have to *hide* a lot of technology. I'd argue that Apple became so successful in part because early on, it became one of the primary vendors of magic. I'll never forget the first time I drew a picture with the mouse on the very first Mac. It was a program called MacPaint—black-and-white only, on a 512- by 342-pixel screen—but it took my breath away.

Apple has often been late to the party. Long before Apple introduced the iPad, other companies sold tablets. Well before the iPod debuted, pocket music players were available from rivals. And before the iPhone was even a twinkle in Steve Jobs's eye, you could buy touch-screen phones.

Why didn't those products set the world on fire? You know what I'm going to say: because they weren't magical.

The early tablets were thick and clunky and covered with buttons; the technology wasn't hidden enough. The early MP3 players were glitchy; nothing says "not magic" louder than the need to troubleshoot. And touch-screen phones weren't truly magical until they had *multitouch* screens like the iPhone's. The first time you tried zooming in on a photograph by spreading two fingers on the glass, you were sold. You *wanted* that product. It was magic that you could buy.

Fortunately, these days magic is everywhere, appealing both to our laziness and to our sense of wonder. It's in wireless charging and augmented reality. It's in voice control of our smart homes and in Fitbits that somehow know what sport you've just played for an hour. It's in summoning a car and driver with one tap on your phone. It's in software that recognizes the faces of your friends in your pictures.

Thank you, engineers and designers of the world, for taking on the role of creating magic. Right now we the people can use all of it we can get. SA

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scientificamerican.com/aug2017/pogue

Illustration by Jay Bendt

life's origins

CHEMISTRY

Deep oceans were thought to hold life's origins. New evidence points instead to an active volcanic landscape

By Martin J. Van Kranendonk, David W. Deamer and Tara Djokic

BIRTHING POOL: Life on Earth could have started in places similar to the Grand Prismatic Spring in Yellowstone National Park.

Martin J. Van Kranendonk is director of the Australian Center for Astrobiology in the School of Biological, Earth and Environmental Sciences at the University of New South Wales. He has conducted research for more than 30 years in extremely old rocks across the planet.

David Deamer is a faculty member in the department of biomolecular engineering at the University of California, Santa Cruz. He is author or editor of 12 books, including *The Origins of Life* (2010), co-edited with Jack W. Szostak, and *First Life* (2011), published by the University of California Press.

Tara Djokic is a Ph.D. candidate at the Australian Center for Astrobiology at the University of New South Wales. Her project combines geologic observations of early evidence of life in Western Australia with virtual-reality technology.

IT'S PITCH-BLACK. WE HAVE BEEN SCRATCHING OUR WAY THROUGH DENSE UNDERBRUSH IN northwestern Australia, guided only by the dim light from a GPS screen. The light is too weak to reveal fallen trees that fill the dry creek bed we are following, and we keep tripping over them. We are two geologists working in a remote region of the country known as the Pilbara: Djokic up front and Van Kranendonk several steps behind. Our truck, parked somewhere on a small plateau, seems a world away. We are not sure if the GPS's batteries will hold out long enough to show us the way back. The night sky, ablaze with countless stars visible right down to the horizon, twinkles in an amazing spectacle as Jupiter dances with nearby Venus. Sadly, this spectacle provides little navigational help for two scientists fumbling their way through the Australian outback in June 2014.

Heading up the side of the creek embankment, Djokic suddenly stumbles back downhill. Has she lost her balance? To stop her from falling, Van Kranendonk reaches out to stop her and pushes her back uphill, which prompts a screech, something unintelligible, and finally a sputtered cry: "Sp- … p- … p- … pppider!" Djokic has not stumbled at all. She is in flight mode, in fear for her life as she tries to swat away the thick spider web enveloping her. Spiders have a deservedly bad reputation in Australia. In the dark, it is not a good idea to assume that you have found the odd benign species.

The reason we are feeling our way around the Pilbara at night is because we had spent the day enthralled by a new discovery Djokic had made in 3.48-billion-year-old sedimentary rocks called the Dresser Formation. Some of the rocks are wrinkled orange and white layers, called geyserite, which were created by a volcanic geyser on Earth's surface. They revealed bubbles formed when gas was trapped in a sticky film, most likely produced by a thin layer of bacterialike microorganisms. The surface rocks and indications of biofilms support a new idea about one of the oldest mysteries on the planet: how and where life got started. The evidence pointed to volcanic hot springs and pools, on land, about 3.5 billion years ago.

This is a far different picture of life's origins from the one scientists have been sketching since 1977. That was the year the research submarine *Alvin* discovered hydrothermal vents at the bottom of the Pacific Ocean pumping out minerals containing iron and sulfur and gases such as methane and hydrogen sulfide, surrounded by primitive bacteria and large worms. It was a thriving ecosystem. Biologists have since theorized that such vents, protected from the cataclysms wracking Earth's surface about four billion years ago, could have provided the energy, nutrients and a safe haven for life to begin. But the theory has problems. The big one is that the ocean has a lot of water, and in it the needed molecules might spread out too quickly to interact and form cell membranes and primitive metabolisms.

Now we and others believe land pools that repeatedly dry out and then get wet again could be much better places. The pools have heat to catalyze reactions, dry

IN BRIEF

To get started, life on Earth needed energy to create complex molecules and ways to bring these molecules together.

A system of volcanic pools and hot springs on land has the needed ingredients for life and wet-dry cycles for interaction and natural selection.

A land-based volcanic origins theory, in contrast to an ocean-focused one, guides us to different places in the solar system to search for life there.

PRECEDING PAGES: WERNER VAN STEEN *Getty Images*

spells in which complex molecules called polymers can be formed from simpler units, wet spells that float these polymers around, and further drying periods that maroon them in tiny cavities where they can interact and even become concentrated in compartments of fatty acids—the prototypes of cell membranes.

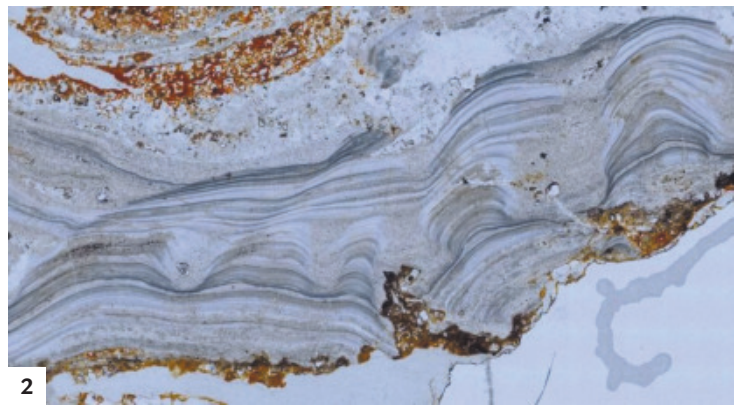
What Djokic found was strong geologic evidence that the Dresser, now a dry, hot and barren outback environment, had once been like the steaming pools and erupting geysers of Yellowstone National Park in the U.S., an active geothermal field. And everywhere in the Dresser there are fossilized signs of life intimately associated with the old hot spring system. Although the Dresser was not the actual site where the most primitive life began half a billion years earlier, it was showing us that hydrothermal environments on land were present very early in Earth's history. Charles Darwin had suggested, back in 1871, that microbial life originated in "some warm little pond." A number of scientists from different fields now think that the author of *On the Origin of Species* had intuitively hit on something important. And the implications of these ideas stretch beyond our own planet: in our search for alien life elsewhere in the solar system, a land-based theory about origins would guide us to different places and planets than would an ocean-based theory.

FROM RUSSIA WITH LIFE

TEN YEARS BEFORE Djokic's run-in with the spider web, another of us (Deamer) had shown that volcanic pools could foster the assembly of compartments made of membranes, essential boundaries of all cellular life. Deamer led a group of scientists to Mutnovsky, an active volcano in the Kamchatka peninsula of far eastern Russia. The group was exploring a prebiotic analogue site, a region that can give researchers a sense of what the planet was like four billion years ago, before life began. Deamer's idea was that simple molecular building blocks might join into longer information-carrying polymers like nucleic acids—needed for primitive life to grow and replicate—when exposed to the wet-dry cycles characteristic of land-based hot springs. Other key polymers, peptides, might form from amino acids under the same conditions. Crucially, still other building blocks called lipids might assemble into microscopic compartments to house and protect the information-carrying polymers. Life would need all the compounds to get started, and Mutnovsky had an abundance of hot springs and geysers in which the idea could be tested.

Deamer had brought a bottle of white powder containing raw material that was likely available on the prebiotic Earth, including four amino acids and four chemical bases that compose naturally occurring nucleic acids, as well as phosphate, glycerol and a lipid. He poured this mixture into the center of a small, boiling spring. Within minutes a white, frothy foam emerged around the spring's edges. The foam was composed of countless tiny vesicles, each containing compounds that were present in the original soup.


1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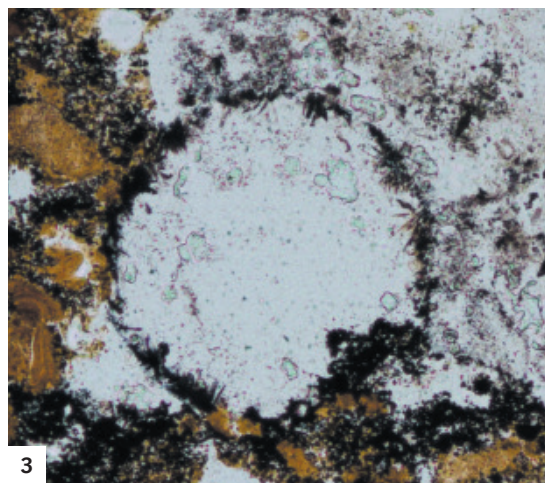
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LIFE ON THE ROCKS: Orange rocks in Australia's Pilbara region are called geyserite, composed of minerals splashing from geysers in hot springs (*1*). The rocks show signature dark bands rich in titanium and light bands composed largely of potassium in a microscopic view (one centimeter in width) (*2*). Minuscule bubbles preserved in this 3.5-billion-year-old geyserite were formed in sticky biofilms, the products of biological organisms (*3*).

If the compartments dried out around the edges of the puddle, could their contents, already in close proximity, join together as polymers? Could this be a stepping-stone to the first life? Back in his laboratory, Deamer and his colleagues tested the idea by mixing simple nucleic acids called nucleotides with lipids. The mixture was put through cycles of wetting and drying under the acidic conditions and high temperatures found in the Kamchatka pool. The result: longer polymers ranging from 10 to more than 100 nucleotides in length. Later studies using x-ray diffraction demonstrated the polymers resembled ribonucleic acid, or RNA. Furthermore, these polymers were encapsulated by the lipids to form vast numbers of microscopic compartments

COURTESY OF MARTIN J. VAN KRANENDONK

called protocells. Though not alive, they were clearly an important step toward life.

Deamer used just a few wet-dry cycles in his experiments and got relatively simple molecules. A colleague of his at the University of California, Santa Cruz, computer scientist Bruce Damer, suspected that many more cycles might add another key feature: the survival of the fittest. Each drying cycle, Damer figured, would cause lipid membranes of the vesicles to open, allowing polymers and nutrients to mix. On rewetting, the lipid membranes would reencapsulate different mixtures of polymers, each mixture representing a kind of natural experiment. More complex protocells would have better chances of survival because their greater variety of molecular mixtures might stabilize the protocells in various conditions—one set of molecules helping in one set of surroundings, another helping in a different set. These intact protocells would then survive to pass on these polymer sets to the next generation, climbing an evolutionary ladder. Damer realized that this model resembled a kind of chemical computer "booting up" the functions of life, starting with random "programs" written in the form of polymers.

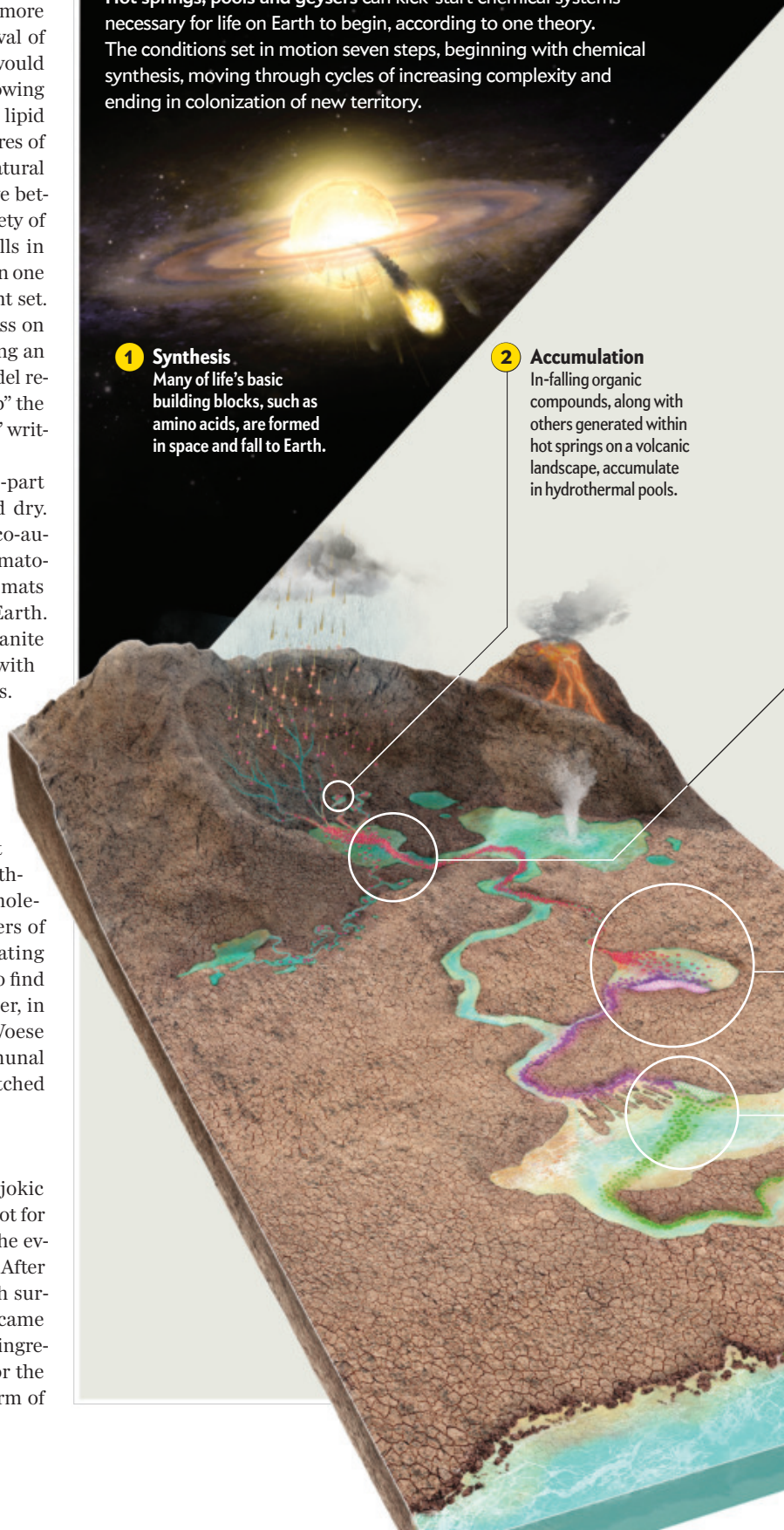
In 2015 Damer added a third phase to the two-part cycle: an intermediate stage between wet and dry. The idea occurred during a field trip with the co-authors to the Dresser Formation in search of stromatolites, which are the fossilized layers of bacterial mats and some of the earliest evidence of life on Earth. Damer was walking through the desert near a granite outcrop known as Gallery Hill that is covered with Aboriginal rock carvings known as petroglyphs. On the way, he noticed brown, dried-up microbial mats in small depressions in the outcrops. Out of curiosity, Damer poured water on the mats, and they sprung back to life, becoming green and gel-like. He realized that if wet-dry cycles in an origin pool also included a moist phase, in which surviving protocells crowd together into a similar gel, polymers and nutrient molecules could mix and exchange across the barriers of lipid membranes. This community of cooperating protocells would have even more opportunities to find the best molecules for survival. Forty years earlier, in fact, scientists George Fox and the late Carl Woese proposed the term "progenote" for such a communal primordial phase of life; Fox told Damer this matched his protocell gel.

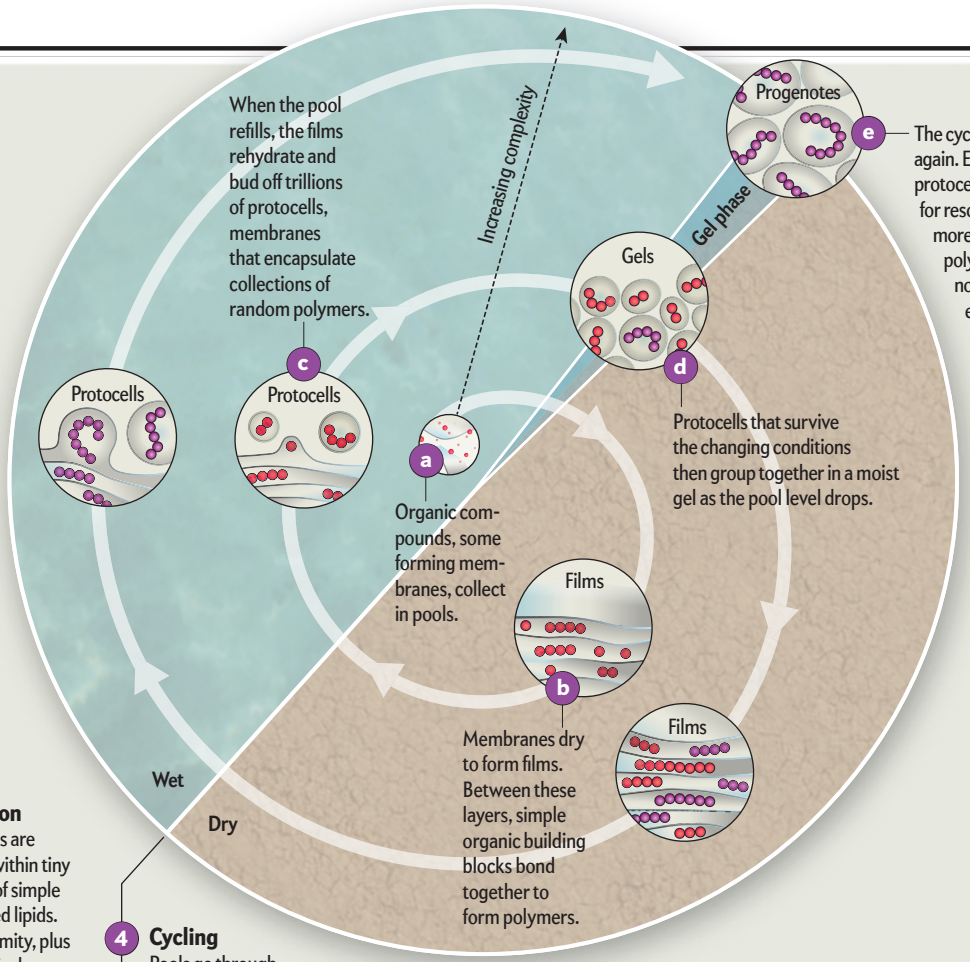
POOLS OF INNOVATION

THE BUBBLES AND MINERAL composition that Djokic found in the Dresser Formation made it a likely spot for the three-part cycle to occur, and we published the evidence this past May in *Nature Communications*. After we realized that the Dresser had been filled with surface hot springs in a geothermal system, it became clear that it also had contained many of the key ingredients and organizational structures required for the origin of life. It had a source of energy in the form of

Genesis Landscape

Hot springs, pools and geysers can kick-start chemical systems necessary for life on Earth to begin, according to one theory. The conditions set in motion seven steps, beginning with chemical synthesis, moving through cycles of increasing complexity and ending in colonization of new territory.





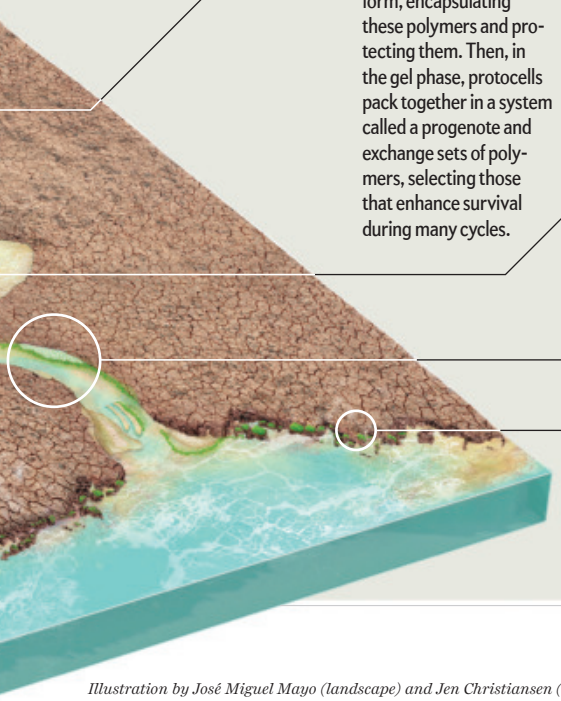
3 Concentration
The compounds are concentrated within tiny vesicles made of simple molecules called lipids. The close proximity, plus heat and chemical energy from the spring system, links them together to form more complex molecular chains.

4 Cycling
Pools go through repeated cycles of three phases: dry, wet and moist gels. Dry times help to synthesize polymers used to carry information, such as chains of nucleic acids. In a wet period, protocells can form, encapsulating these polymers and protecting them. Then, in the gel phase, protocells pack together in a system called a progenote and exchange sets of polymers, selecting those that enhance survival during many cycles.

5 Distribution
The best-adapted protocells spread to other pools or streams, moving by wind and water, and some develop the ability to use carbon dioxide for photosynthesis. After much trial and error, one protocell assembles the complicated molecular machinery that enables it to divide into daughter cells. This paves the way for the first living microbial community.

6 Adaptation
Some of these early microbes are pushed into saltwater estuaries, beyond their native freshwater ponds. The microbes that survive pass along useful traits that help descendants expand their range to oceans.

7 Colonization
Sea storms and tugging tides select for mats of rugged microbes able to cement themselves together using grains of minerals. These layers pile up into stacks called stromatolites. Life continues to expand into other niches, setting the stage for free-living cells. After billions of years, these organisms evolve into complex multicellular plants and animals.



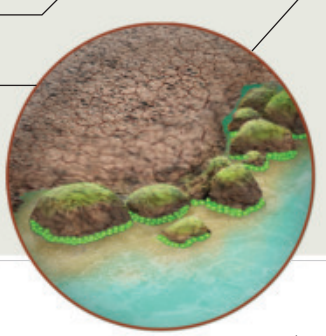


Illustration by José Miguel Mayo (landscape) and Jen Christiansen (cycling detail)

Journey to a Land across Time

When I first set foot in Western Australia's Pilbara, a landscape holding 3.5-billion-year-old clues to the beginning of life, I was very disappointed. The year was 1994. I drove excitedly out of the west coast town of Port Hedland, but all I saw for the first 150 kilometers were a few withered, scraggly trees and smoky dust devils traipsing across the burnt, flat plain. I felt desolated. What had I gotten myself into? And the heat!! I'd never experienced anything this brutal before. Or breathed air so thick with biting flies.

But as we continued to head south on the highway to Marble Bar—the hottest town in Australia—some low, broad hills started to rise from the horizon. We started to cross sandy creeks and rivers, including the mighty Shaw, whose banks were garnished with lush-looking coolabah trees, with their distinctive, bright-white trunks.

As we continued down a dirt track into the hills, the burnt plains gave way to grass-covered hummocks. This grass is called spinifex, an amazing but devilish creation. It grows as bushes up to one meter in diameter, with round, fine blades that taper into needle-sharp tips made almost of pure silica. The tips will penetrate through just about any piece of fabric. My supervisor whipped out thick gaiters to protect his legs. But he had failed to inform me of the hazard. Without any gaiters, I was a walking porcupine within minutes—my skin skewered with multiple silica needle tips that broke off and remained in my flesh for months.

The land, ultimately, proved worth the discomfort. Here I was walking over some of Earth's oldest, best-preserved rocks that contain evidence of life from almost the very beginnings of time on our planet. As I looked at some wrinkly structures that lay above the ripples of ancient sediment, I realized I was looking at remnants of our great-, great-, great-grandparents—the precursors to all complex life on Earth!

CRADLE OF LIFE? Australia's Pilbara region, now dry, once held hot springs and geysers.

This area had changed much from when it was first formed 3.5 billion years ago. Back then it would have been a black volcanic land, with no color from vegetation. Over the hills I might have glimpsed a green, iron-rich sea underneath an orange sky heavy with carbon dioxide and devoid of oxygen. Nearby in the landscape I'd come across fields of hot springs, and here I'd start to see some color. There would be stretches of white and yellow and red around bubbling mud pools and splashing geysers, the colors of sulfur, clay and iron. And in some pools and channels, perhaps there would have been strands of beige, red and purple: colonies of heat- and chemical-loving microbes. There might even have been some green from very early photosynthesizing organisms.

If I were able to ride a time machine forward a billion years, I'd see the Pilbara become buried under kilometers of volcanic lavas and sediments; I'd see the landmass move across the face of the globe and run into other pieces of crust, the collisions forming mountain belts. At about 2.5 billion years ago, I'd see the oceans fill with life, the shallow coastal areas occupied by huge reefs made of primitive microbes called cyanobacteria that stack in piles of mats called stromatolites. The sky would turn blue as the photosynthesizing cyanobacteria sucked in carbon and pumped out oxygen into the atmosphere. Almost another two billion years later the world would turn cold and become covered in a global ice sheet, wiping out almost every living thing. When it melted away, oxygen levels rose again. Life really got going. Animals slowly colonized the land, as did new types of plants. The greening of our planet began in earnest, and a wide variety of organisms appeared—including, unfortunately for me, spinifex.

—M.J.V.K.

circulating hydrothermal fluids, rich in hydrogen, heated by magma from below. The rocks contained abundant amounts of the element boron, a crucial ingredient in the synthesis of ribose necessary for nucleic acids such as RNA. The Dresser also has phosphate minerals that dissolve out of the underlying rocks and join circulating acidic geothermal fluids. Phosphate is an important component of nucleic acids, but it is also used by all life in the form of ATP (adenosine triphosphate, the molecule that supplies energy within cells). In addition, there were high concentrations of zinc and manganese, components of many enzymes in the cytoplasm of cells from all known branches of life, found in hydrothermal vents and in evaporative volcanic lake deposits. Finally, the Dresser also had clays, which can function as catalysts for creating complex organic molecules because of the electrically charged layers of mineral surfaces they contain.

Perhaps the most exciting thing about the Dresser as an origin analogue site is its amazing variety because in this field of science, variety is very much the spice of life. The Dresser is dry and rocky now, but in their youth, geothermal hot spring fields such as this one contain many hundreds of pools, each with a slightly different pH, temperature, dissolved ions and other chemical variations. Chemical complexity is rich in such fields because they contain three highly reactive interfaces—between water and rock, water and air, and rock and air. The fields also have different temperatures at different spots. Multiply all of this together: the wetting-drying cycles happening multiple times each day (think Old Faithful in Yellowstone), variable

THEO ALLOFS *Getty Images*

pool chemistries, highly reactive interfaces, the ability of pools to exchange compounds as geysers splash their contents back and forth, and an interconnected, fluid-filled, subterranean fracture network. When you do the math, it looks as if a terrestrial geothermal field of 100 springs can generate a million or more new combinations of conditions every year!

Each warm pond becomes an "innovation pool," a test bed in which adaptive combinations of molecules rapidly emerge and find ways to grow and reproduce or in which maladaptive combinations fall by the wayside, unable to keep up. It is likely that immense numbers of combinations might have been required to assemble the first primitive version of life, in which case the process would take hundreds of millions of years. But the numbers of combinations in terrestrial geothermal fields suggest that life could have originated and begun to evolve in as little as 10 million years, with the first stages beginning as soon as there was a stable crust peppered with volcanic landmasses amid the oceans, just more than four billion years ago.

VENTING DISAGREEMENT

NOT EVERYONE AGREES that surface hot springs are the most likely sites of life's beginnings. The deep-sea vent hypothesis is still alive and kicking. At NASA's Jet Propulsion Laboratory, biochemist Mike Russell has developed *Alvin*'s original discovery of hydrothermal vents into an alternative, elegant—but as yet unproven—model. In his scheme, mineral membranes that form minuscule pores within vent rocks initially separate alkaline water from more acidic ocean water. This produces a gradient of several pH units, similar to the difference between a solution of household ammonia and a glass of orange juice. The gradient is a form of energy that can be tapped; modern bacterial cells do exactly this to generate the ATP they need. There is another source of energy in the vents in the mixture of dissolved gases such as hydrogen and carbon dioxide. Russell and his colleagues have proposed that when carbon dioxide in ancient seawater mixed with hydrogen coming from the vents, the transfer of electrons from hydrogen to carbon dioxide could synthesize more complex organic compounds. In their view, the mineral compartments resemble cells, and the energy of pH gradients and hydrogen could ultimately evolve into a primitive metabolism required by the earliest forms of life.

The hot spring field and deep-sea vent hypotheses have some far-flung implications. Beyond guiding further explorations of life's beginnings on Earth, they point to different approaches to search for life on other planets and their moons. If the deep-sea vent origins theory is correct, the icy ocean worlds of Enceladus and Europa may be good places to look. On the other hand, if our model of fluctuating hot springs is right, then these worlds are unlikely to host life.

What about Mars? Although there is good evidence for shallow seas on Mars in the distant past, there are few signs of a global ocean or of tectonic spreading zones that create hydrothermal vents on Earth. If life depended on vents to begin, it was unlikely to have begun on the Red Planet. But if life on Earth originated in terrestrial hot springs, it could have also begun on Mars, which had the hot spring ingredients of widespread volcanism and water. Indeed, in 2008 the Spirit rover discovered 3.65-billion-year-old hot spring deposits in the Columbia Hills on Mars, about the same age as our Dresser hot springs, which did a great job of preserving early evidence for life on Earth.

Both the deep-sea vent and the land-based hot spring pools models have a long way to go before either can be deemed correct. The origin of life is like a jigsaw puzzle with many different pieces, and we do not know enough yet to put each one in the proper position. At the Dresser Formation, for instance, we do not understand what causes certain elements to become concentrated in different pools, how geothermal fields evolve over time, or how their different chemistries interact to synthesize or degrade organic molecules. We need to construct more sophisticated experiments of prebiotic chemistry in a series of warm little pools, studying how complex organic molecules form and how they interact and combine when encapsulated within membranes.

Both on land and in the sea, chemical and physical laws have provided a very useful frame around this particular puzzle, and the geologic and chemical discoveries described here fill in different areas. But before we can see a clear picture of the origin of life, many more pieces need to be put in place. What is exciting, however, is that now we can see a path forward to the solution. SA

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FROM OUR ARCHIVES

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FISHERMEN on the choppy Sea of Cortez haul in corvinas. Fishing has been blamed for killing off the vaquita, but organized criminals and corrupt government officials are also suspect.

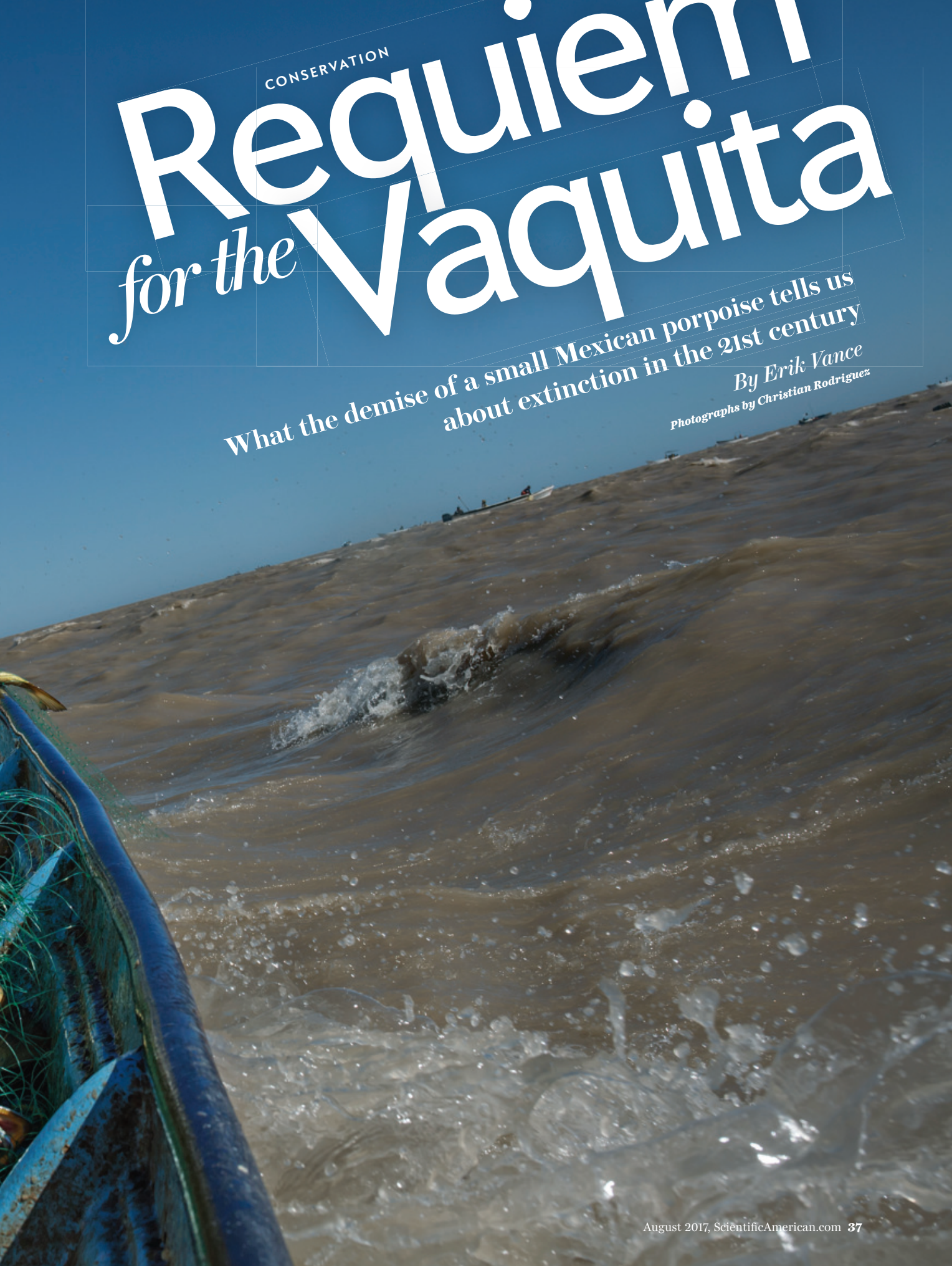
CONSERVATION

Requiem for the Vaquita

What the demise of a small Mexican porpoise tells us about extinction in the 21st century

By Erik Vance

Photographs by Christian Rodriguez



Erik Vance is a freelance writer in Mexico City who covers the environment and neuroscience. His first book, *Suggestible You* (National Geographic, 2016), is about how belief affects the brain.

VAQUITAS, tiny porpoises, are about as big as illegally fished totoabas, so they get snared in the totoaba nets and die.

NIGHT IS FALLING on the northern Sea of Cortez. It is eerily still. The terns and pelicans have gone to roost, and the dolphins no longer crisscross the water by the hundreds. The sea lions have hauled out for the evening. The usually temperamental water, the color of chocolate milk, is smooth as glass. Sundown is the best time to be on the upper Gulf of California, as the sea is also known, wedged against the Mexican desert, close to the U.S. border. The searing sun gives way to fantastic swaths of oranges, pinks and reds, painting the water with dancing shimmers of failing light.

Looking out, I almost forget I'm on the deck of a boat flying a pirate flag, wondering if it might suddenly be boarded by angry, armed fishermen. Nick Allen, a bosun mate of this 180-foot-long vessel operated by the Sea Shepherd Conservation Society, is pulling up an illegal 4,000-foot longline. So far the line has produced a couple of dead eels and an endangered hammerhead shark. But then the real prize appears. "Totoaba!" he yells. "There, *there!*"

The hooked fish, still alive, is about four feet long, shaped like a blimp and worth several thousand dollars. Energized, the Sea Shepherd team prepares to set it free. For the past four months the 20 or so people onboard have been removing nets that litter the upper Gulf. Since they began, they have extracted over 100 abandoned riggings and dozens of dead totoabas, sea lions and other protected creatures. Almost every night their radar tracks fishermen laying new nets from skiffs that easily outrun local law-enforcement boats. During the day team members send out drones that watch poachers scope out places to put down illegal nets, practically under the noses of nearby authorities, as if it was just another morning on the water.

Yet the environmentalists are not interested in the totoabas, really. They are here for a very small porpoise whose extinction is all but inevitable. Often called the Gulf porpoise, local people just call it the *vaquita,* or "little cow." Too often vaquitas get tangled in the nets meant for totoabas, and they die. "Whoa! There he goes! There he goes!" someone yells as the hulking fish bucks free and disappears into the turbid sea the moment the hook is cut. "Yeah, that one was definitely healthy."

Sea Shepherd crews are rarely a welcome solution to any fishery problem. Famous for chasing Japanese whaling ships across the Arctic Ocean, they are the activists of last resort. Hated by fishing communities the world over, the arrival of Sea Shepherd usually means that every diplomatic effort at conservation has failed. Nowhere is this more true than in the upper Gulf.

The Sea of Cortez is among the most impressive ecosystems on earth. Almost 1,000 species of fish live here, 10 percent of which are found nowhere else. Half of Mexico's commercial fishing haul comes from this sea. But environmentalists and local fishermen are chronically at odds. For the past three decades they have butted heads in a cycle of blame, corruption and occasional violence over the vaquita. Just a day before, in an attempt to stop the illegal activity, federal officials announced that the fishing season was canceled for another year, causing fishermen in a town a few miles to the east called El Golfo de Santa Clara to riot, incinerating 10 government trucks and several boats and beating fisheries agents.

To complicate matters, drug traffickers are partnering with illegal fishermen to control the flow of totoabas across the U.S. border. Death threats against officials or environmentalists are an almost weekly occurrence; at least two fishermen have been gunned

IN BRIEF

Only 30 Gulf porpoises, or vaquitas, remain, all in the Sea of Cortez. For years they have died after being caught up in fishing nets, many illegal, intended for animals called totoabas. **Failed government oversight** of fishing rules, a battle among scientific camps, organized criminals who sell totoaba swim bladders on the black market and Mexico's inability to work with fishing communities doomed the vaquita. **Dozens of other species,** from snow leopards to elephants, also face complicated threats. Biologists cannot save them. Government leaders who can improve local economies must do the job.

FLIP NICKLIN *Getty Images*

MEXICAN MILITARY personnel confront a lone fisherman who they said had unlawfully cast a net from the Santa Clara shore. Yet organized poachers regularly slip through law enforcement's grasp.

down in the past few years. Once peaceful fishermen now go to sea heavily armed and share trade routes and profits with drug kingpins. With stories rampant of methamphetamine laboratories near fishing camps and of drug lords in trucks by the shore firing on police to defend poaching boats, tourism has slowed to a crawl.

"Fishing should be banned in the Sea of Cortez," says Oona Layolle, architect of the Sea Shepherd campaign. "Seas like this that are so fragile, with such a huge ecosystem—with the number of people on earth now—they should be protected."

Meanwhile the official number of vaquitas has dropped to just 30. In a last-ditch effort to save the animals, a joint U.S.-Mexico team plans to catch as many of them as it can find and keep them in captivity.

The vaquita, close to joining the ranks of the passenger pigeon, represents one of the most dramatic failures in wildlife management today, and its story has crucial lessons to teach us about the nature of extinction in the modern world. The creature was not destroyed by settlers, like the hapless dodo bird was, or by rampant human development, like the Chinese river dolphin was.

Unlike the Siberian tiger or white rhino, it has no commercial value. What killed the vaquita was a lethal mix of greed and corruption, meager government oversight, an entrenched battle between scientific camps over why the species declined in the first place and the inability of Mexico to harness the goodwill of fishermen. Although these lessons may come too late for the vaquita, they could save countless other species on the brink of extinction worldwide.

THE VAQUITA, discovered relatively recently, was not always a flash point. In 1950 legendary marine biologist Ken Norris was wandering the upper Gulf beaches when he stumbled on a porpoise skull lying in the sun. It was oddly shaped and very small. Eight years later he published a paper introducing the Gulf of California harbor porpoise, although he had never seen a live specimen.

For the next couple of decades the animal was almost a ghost, seen only a few times when scientists would find one washed up next to a fishing village. Researchers wondered whether the local totoaba fishery might be threatening the vaquita's survival. The

SOURCES: NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (*marine reserves*); NATIONAL GEOGRAPHIC (*Colorado River*)

Map by Mapping Specialists

totoaba is a highly prized fish that congregates near Santa Clara every spring to breed in the nutrient-rich waters there. A little over 100 pounds, the totoaba is as big as the vaquita, which is itself two thirds the size of a typical porpoise. So it is not surprising that the same gill nets snare both.

By 1975 scientists were actually worried about the totoaba population crashing, so Mexico banned its fishing. Three years later a new Mexican law protected vaquitas, too, despite the fact that few people other than fishermen had ever run across them. Unlike the sassy dolphin or nosy sea lion, the vaquita hates boats and avoids humans at all costs, and it is hard to save an animal that scientists know nothing about. That changed in 1985, when biologist Alejandro "Waffles" Robles arrived in Santa Clara. Then a young, passionate graduate student at the Monterrey Institute of Technology and Higher Education's campus in Guaymas, he was ostensibly there to determine if totoabas truly were endangered or if the fishery should be opened again. But secretly, he wanted to find the elusive Gulf porpoise. He soon discovered that it was impossible to untangle the fate of one from the other.

Waffles quickly found local totoaba poachers just offshore from a fisheries enforcement officer. Rather than stopping or arresting the poachers, the officer was watching over them as they pulled out their catch. Back then, the fishermen were not suspicious of biologists and invited Waffles onto their boats to help raise their illegal nets. One spring day they hauled out a shocking cache—two adult vaquitas and two juveniles. Seeing an entire family dead "was a very sad moment for me," says Waffles, a robust and otherwise jovial man now in his late 50s. "But I knew the value of those specimens."

All Waffles could think about were the many questions the animals might answer once in a lab. The smallest cetaceans in the world had wide, black rings around their eyes and mouths, as if heavily drawn with lipstick. What use were facial markings in water with zero visibility? What did the creatures eat? Was this family healthy, or was it affected by pollution? The local fishing cooperative let him freeze the animals at its facility, and he grabbed the two adults and got on a bus for the 10-hour trip south to Guaymas, where biologists at his institute could properly examine them. When he boarded, lugging two heavy, wrapped corpses, the driver eyed him suspiciously and asked what on earth he was bringing on the trip.

"Vaquitas," he replied.

"Ah, like ironwood?" the bus driver asked, referring to a hard type of wood used in the region for sculptures.

"Um, yeah," Waffles said as he took a seat. He had forgotten about a customs checkpoint on the way, however. To the driver's horror, the officers pulled a pair of defrosting animals out of the bus and demanded to see paperwork for them. Waffles presented a permit for whale bones, praying the agents did not look too closely. They were baffled and dithered as the passengers got increasingly angry with the delay.

"So I said, 'Okay, guys, if you want them, just take them,'" Waffles recalls. "But the customs agents say, 'Well, what do we want these things for? Okay, you can go.'"

The mutually beneficial relationship between fishermen and scientists continued for years. Mexican and U.S. biologists who performed necropsies confirmed that the mammals were bottom-feeders and bred only once every two years. But one crucial question lingered: Why were there so few of them? The obvious answer was totoaba fishing nets because every specimen had been found dead in them.

Yet that line of reasoning ignored a very large elephant in the room—the Colorado River. For nearly a century the U.S. had built dams along the Colorado to divert water for agriculture and expanding communities. By the 1980s the river was so low that it no longer reached the Sea of Cortez, cutting off the upper

MUTILATED TOTOABA is discarded on the dried-up Colorado River bed. Fishermen catch the protected species and rip out the swim bladder. Racketeers ship the bladders to China, where they sell for thousands of dollars on the black market because they supposedly have potent medical powers.

Gulf from freshwater that had flowed for millennia. Hundreds of miles of mesquite and estuary ecosystems at the now dried-up confluence turned to dust and salt. Scientists wondered if it was a coincidence that one of the most prominent extinctions in North America was happening just a few miles from one of its most devastating environmental catastrophes.

Manuel Salvador Galindo Bect, a retired oceanographer then at the Autonomous University of Baja California, was convinced of a connection, pointing to decimated shrimp populations in the upper Gulf. The shrimp problem "happened almost at the same time as the vaquita issue," he notes. At first this scientific question was little more than a curiosity. Soon it would become the centerpiece of a high-profile political battle that doomed action to save the vaquita.

NECROPSIES WERE THE PRIMARY TOOL scientists had to determine if any changes in the upper Gulf were harming the shy porpoises. The king of necropsies was Jorge Torre, then at the Monterrey Institute. "If you give me a catalogue number, I know which vaquita it was. Number 930206 was a pregnant female," he says with obvious pride. "It was my life—five years, so deep in the insides of the vaquita."

Torre found that male and female vaquitas have differently shaped hyoid bones, suggesting distinct types of vocalizations for each. He and others revealed that the vaquita has an extra digit on its "hands," thus widening the flippers, although no one quite knows why. And so the research went. Vaquitas were endangered, certainly, but not something that fishermen or the wider public thought much about.

Then things changed. Around this time the North American Free Trade Agreement (NAFTA) was being crafted. Negotiations for the agreement began in 1990, and Mexican president Carlos Salinas quickly saw that one of the biggest problems with public opinion would be NAFTA's negative environmental impacts. After talking with experts, including the famous oceanographer Jacques Cousteau, Salinas fixated on the vaquita. Protecting this little porpoise in crisis, right next to the U.S. border, would be a showpiece of his commitment to environmental stewardship. Overnight, the vaquita became a political football.

"I had all these people calling me and asking, 'What do the vaquita and totoaba have to do with free trade?'" Waffles says. "I was a biologist who hardly knew what free trade meant."

In a very public show of environmental stewardship, Mexico designated an oddly shaped vaquita marine reserve in the upper Gulf. The park became the first step in a souring relationship between scientists and the community. Biologists needed the fishermen to turn over specimens for study. But doing so in the park was now a crime. At least on paper. The park had no management plan, no regulations and no one to enforce them. Large fishing trawlers were theoretically banned, but years later they were still there. Local fishermen had no idea what the rules were.

As a result, people assumed that the rules were not serious. To this day, not a single fisherman or broker has been jailed for poaching. Part of the problem was that Mexico City was sending two very different messages. The country's chief environmental agency, SEMARNAT, said the endangered vaquita needed protection. But the fishing industry's representative agency, currently known as CONAPESCA, said it was commercial fisheries that required protection. It once even implied, bizarrely, that the vaquita did not exist—that the creature was either extinct or a fiction created by American environmentalists, a refrain that continues today in some towns.

The misinformation got so bad that scientists presented a dead vaquita to the secretary who oversees agriculture and the

CREWS MAY UNLOAD their bounty at night, depending on the tides. Some fish corvinas legally, some do so illegally and some bring in banned totoabas guarded by armed outlaws in trucks. Law-enforcement officers may struggle to determine who is doing what, or they may look the other way.

environment on a dessert cart during a fancy breakfast meeting just to prove the animal was real. So CONAPESCA pivoted to the empty Colorado River, blaming the vaquita's decline on greedy Americans and their dams. But necropsies revealed no signs of disease or starvation. As it turned out, the vaquita adjusted well to changing food supplies.

Galindo Bect, the Autonomous University of Baja California oceanographer who had become the primary spokesperson for the Colorado River camp, now acknowledges he has no direct evidence that the vaquita is being affected by the river's condition, but he says that is only because the correct tests have not been done. Fishermen are quick to cite him. "I know Dr. Galindo," says 25-year veteran Mario Alberto. "The vaquita problem is not a fisherman one—it's an environmental one."

By 1999 vaquita numbers were still decreasing. As new reserves were proposed, acrimony increased. After Mexico's central government put a temporary hold on upper Gulf finfish, assuming the finfish nets were catching vaquitas, Santa Clara fishermen burned several government trucks and staged a symbolic kidnapping of local officials, who then had to be airlifted out.

Amid the chaos, a third theory arose to explain the animal's decline: inbreeding. Proponents claimed that certain "lethal" genetic combinations will pop up in a small population and cause widespread mortality. It had happened in Scandinavia, where isolated populations of snakes and wolves were vulnerable to genetic diseases. National government officials used this argument to say the vaquita "was doomed to extinction," says Lorenzo Rojas Bracho, a scientist who worked on vaquita genetics in the late 1990s and now helps to run a multinational vaquita group called CIRVA that advises the Mexican government. But Rojas Bracho looked at 75 vaquitas provided by fishermen and determined that the animals were not in danger from inbreeding. Because the population had always been small and isolated, the species had already purged any lethal genes, it seemed. If the animals could be spared the fisherman's net, they could theoretically recover.

Since then, Rojas Bracho has become one of the most pugnacious advocates for the vaquita, making it his mission to battle what he sees as a deluge of misinformation from groups such as CONAPESCA. "I haven't been in a meeting in 20 years where there's not fisheries guys who say [the problem] is lack of flow from the Colorado River," he says. Often these meetings turn into yelling matches.

Rojas Bracho does not trust Galindo Bect and his ties to fishing interests. Galindo Bect does not trust Rojas Bracho's science. The only thing that everyone has agreed on is that illegal totoaba fishing had gotten out of control. By the early 2000s the fishermen, once the key link to specimens, had become the enemy.

NOT THAT THE GOVERNMENT was always against the fishermen. In 2007 it offered money to individuals who turned in their fishing permits so that they could have capital to invest in ecotourism. Build hotels, they were told, and visitors would flock to the upper Gulf. But no one ever asked if tourists wanted to come. Mario Mora Rodríguez, a fisherman of 20-plus years, was among those who took the deal. He says he honestly believed he was working to save the vaquita while providing a future for his family. He built a series of bungalows called the Tourist Cabins. No one came. Today the place sits empty, next to four other vacant hotels. Most of his kids have moved away in search of work.

Eventually the government, through CONAPESCA, awarded

INDIGENOUS COCOPA—the only people issued corvina permits—say that outsiders somehow obtain permits as well and disguise themselves as Cocopa so they can pursue corvinas and totoabas unaccosted.

new permits to different fishermen, who often defied the reserves. By 2008 scientists using underwater listening devices detected just 245 vaquitas left, which meant that since the 1990s, their numbers had been dropping by about 8 percent a year.

From 2008 to 2010 the rate of decline slowed, momentarily raising hopes. But an escalating drug trade erased every possibility of a comeback. President Felipe Calderón declared war against the Mexican cartels, kicking off one of the bloodiest periods in the nation's recent history. The cartels diversified their businesses to include video piracy, prostitution, kidnapping and, in northern Baja, totoaba smuggling. "We noticed that the places where totoabas were trafficked were the same as the places where the Sinaloa cartel operates," says Andrés Estrada, an independent journalist who has spent months in fishing communities tracking the totoaba trade. "The transferring routes were very similar."

The trade had nothing to do with seafood. Totoaba swim bladders had become a popular ingredient in Chinese medicine. Because the original source of bladders—the Chinese bahaba—was near extinction, brokers had begun looking to Mexico, paying $10,000 per kilogram for the stuff. Poachers were cutting into the fishes' bellies onshore, pulling out the swim bladder and leaving the big animals on the sand to rot in the sun.

Estrada and two brave colleagues, Alejandro Melgoza and Enrique Alvarado, have recently reported that not only are drug traffickers moving totoaba bladders across the border to Los Angeles for shipment to China, but armed men now guard the fishermen as they bring their catch onshore because bladders are comparable in price to cocaine or methamphetamines. Totoaba poaching has been fully integrated into organized crime, as drug use has become rampant among fishing communities.

"There are no punishments, no sentencing," says Estrada, who regularly sees armed men selling methamphetamines to fishermen while guarding them as they unload their boats. The people charged with policing poachers are not trained to identify body parts such as swim bladders from particular animals. The environmental police, who can do so, do not have the authority to write tickets or make arrests. When I visited the area, I saw CONAPESCA officers charged with monitoring the catch simply wave trucks of fish by with barely a glance, just miles from where totoaba carcasses littered the beaches.

In 2014 Samuel Gallardo, one of the heads of a fishery cooperative, was reportedly gunned downed by a rival to the Sinaloa cartel, presumably because of a dispute over smuggling routes. A couple of years later another fisherman, José Isaías Armenta, was shot to death by local cops. The official explanation is that Armenta was shot while he was resisting arrest, although locals in Santa Clara, who did not want to be quoted, say it was because he refused to pay bribes related to the totoaba trade.

BETWEEN 2011 AND 2015, after years of slow decline, the vaquita population plunged by 60 percent. In a final effort to save the creature, the Mexican government in 2015 declared a two-year moratorium on all gill-net fishing in the upper Gulf, including for shrimp and a smaller fish called corvina. Though less valuable than shrimp, corvinas accounted for hundreds of jobs in the upper Gulf, from the fishermen who catch them to the townspeople who clean them and prepare them for shipment.

Previously, individuals with corvina permits drove the local economy. The government now pays them almost $2,000 per month, per permit, not to fish. But only the wealthiest fishermen could afford a permit, so only a few people in town have them. Fishermen who worked for them get about $400 per month, far short of what is needed to pay basic monthly bills. And people who were once employed onshore to clean fish get nothing. In other words, the government is paying the wealthiest people in town a fortune while the poorest must fend for themselves.

Enrique "Gringo" Assaf, who owns seven permits and employs 12 fishermen, says the government pays him about $10,000 a month not to send out his boats. He has used the money to build a hotel and start an all-terrain vehicle rental business. Assaf blames the government for the unequal payments to the fishermen as well as for bungling the conservation plans.

In March the government announced another year of canceled permits, extending the moratorium. That is when fishermen took to the streets, burning those federal trucks—although they insist the real spark was a crooked federal agent trying to skim money. "You don't know what's going to happen tomorrow or the day after," says former fisherman Alfonso Pita. "I have a wife, a daughter and another daughter who's a single mom with two kids. What am I going to do? The little money I had, I invested in the boat." For him and his daughters, there are no jobs.

The corvina has delicious meat, and its bladder can be sold to China, too, though at a fraction of the price of totoaba bladders. But because of the moratorium, no one has permits to fish corvinas except for the Cocopa, members of an indigenous community to the north. Mexican officials and environmentalists say that many of the illegal totoaba fishermen somehow obtained Cocopa permits and are disguised as Cocopa corvina fishermen. "We were invaded by outsiders," says Inés Hurtado Valenzuela, one leader of a Cocopa fishing cooperative. She points out that if the Cocopa were to fish for the totoaba, they would certainly eat it rather than just pull out the swim bladder and leave the animal to rot, as poachers do.

It is not hard to verify what she says. She offers me a ride to see where the Cocopa fish. A few miles south of town, the landscape turns from scruffy mesquite to barren mudflats and salt pans—the devastation caused by the dammed Colorado River. Yet a sprawling ad hoc village appears in the middle of this wasteland. Hundreds of fishermen bring in corvinas along a channel that connects to the Gulf. As we ride along the channel, a dead totoaba floats by, its innards ripped out. Farther down are dozens more, hurriedly butchered and discarded. There is only one place along the channel to bring out corvinas (or illegal totoabas), but when we pass the CONAPESCA checkpoint there, the officials barely glance at the corvinas in the back of our truck.

All the while, the vaquitas keep disappearing. From 2015 to 2016, they dropped by another 50 percent, to an estimate of just 30 individuals. Five were found dead in the spring of 2017.

ACTIVIST HILDA SOMOZA (*in white shirt*) organizes petitions from Santa Clara residents who formerly cleaned and packaged fish. The government pays individuals who had corvina permits not to sail—an attempt to slow the ocean take—but offers nothing to onshore workers, who have no other jobs. A Santa Clara fruit vendor painted a mural to remind people that amid the infighting and crime, vaquitas trapped by nets are the innocent victims. "Their faces look happy," he says, "but they are dying."

IT IS EASY TO ASSIGN BLAME for the vaquita's extinction. It is the fault of CONAPESCA for refusing to push the fishermen. It is the fishermen not calling out the poachers in their midst. It is SEMARNAT refusing to seriously protect endangered species. It is the enforcement agencies sitting on their heels. It is the government in Mexico City establishing reserves on paper (three of them now) that are meaningless at sea. It is the Americans taking water from the Colorado River. It is the biologists and conservationists constantly blaming powerless locals. It is the powerful locals keeping everybody else poor. It is the Chinese creating the market in the first place. It is the drug cartels ramping up poaching.

Regardless of who is responsible, the vaquita is more than just a lonely animal watching its own sad demise in the turbid Gulf waters. Rather it is a harbinger of extinction in the 21st century. No one can say which animal will be the next to disappear, but we can describe it. It will come from a small, isolated population. It will be a highly lucrative creature or will be connected to one. And it will live in a developing country that has failing institutions.

Experts cite dozens of other species that are facing problems similar to the vaquita's. The Ganges River dolphin is a geographically limited species with a habit of getting tangled in nets; it has declined by more than 50 percent in 60 years to fewer than 2,500 today. The daggernose shark from northern South America has dropped by 90 percent in 10 years, thanks to slow reproduction and poorly regulated mackerel fishing.

Local cashmere herders in Central Asia randomly kill endangered snow leopards to preserve their goats, which feed luxury markets abroad. Rhinos, elephants and helmeted hornbills are all valuable creatures, traded from Africa and Indonesia to Asia by criminal networks that exploit weak local institutions. Pangolins—small, scaly mammals—are seized by poachers in Asia and sold right there, on the black market, in collusion with the government.

In a sense, the vaquita has been caught in the same problem that has choked much of Mexico and the developing world. The

country simply does not have the ability to enforce all its laws, especially in the face of organized crime.

A harder lesson to accept may be that even though it is easy to think of the vaquita as a treasure belonging to the world, it really belongs to the local fishermen. They were the first to see it, they named it, and they provided samples and freezers to the scientists, who informed lawmakers, who, in turn, passed the laws to limit fishing. Without their help, vaquita conservation is hopeless.

The greatest mistake conservationists made, therefore, was sending biologists to do a social worker's job. Catalina López Sagástegui was one such biologist. In 2006 she was an idealistic scientist thrilled to be involved with marine mammal conservation. After working on gray whale initiatives near Baja, she headed to the upper Gulf. López Sagástegui quickly saw that vaquita conservation was not a typical project. Fishermen were regularly yelling at one another and walking out of meetings. She was confused and fascinated: Why couldn't they find the answer that could help them move forward?

Being a part of the community for 10 years, López Sagástegui has realized that the problems threatening the vaquita have nothing to do with science and everything to do with human behavior. She says she and many others were ill prepared to deal with the forces in play: "Conservationists are not social development experts. I can't believe we have 30 vaquitas left, and yet we have the same [old] proposals." Now at a cross-border institution called the University of California Institute for Mexico and the United States, López Sagástegui says the government and conservation organizations have been trying to wave a magic wand that will convert fishermen into something else without having any idea of what that is. Rather than setting out what the fishermen could not do—use gill nets, fish for totoabas—they should have focused on creating business opportunities and designing sustainable strategies.

TODAY NO GOOD OPTIONS ARE LEFT, save one. In a desperate last effort, this October biologists from Mexico and the U.S. will use trained navy dolphins to round up as many remaining vaquitas as possible, capture them and breed them in captivity. Although captive breeding has saved land animals such as the California condor, it has never been successfully done with marine mammals. And no one has ever caught a vaquita on purpose, let alone kept any alive long enough to reproduce.

It is possible that, like its cousin the harbor porpoise, the vaquita will be suitable for capture and will transfer easily to captivity. It is equally possible that it will not. If captivity fails, "then, well, we tried," says Barbara Taylor, a marine biologist at the National Oceanic and Atmospheric Administration, who is helping to direct the navy project and has spent her life studying endangered cetaceans. "It's game over." An entire species now hinges on 30 individuals and a Hail Mary plan to put them behind glass.

This final attempt will happen without the help of those first vaquita scientists. Many of the earliest warriors have burned out on the vitriol and politics of the battle. Exhausted with the gridlock, Torre and Waffles quietly turned away from the slugfest and found work elsewhere. Ironically, they both now practice a new and stunningly successful form of conservation in Mexico.

In 1999 Torre, the master of dissection, co-founded a nonprofit called COBI to revive lobster and other commercial fisheries. His team begins each process with the needs of the local fishermen rather than of the animal. Long before anyone utters the word "conservation," they have dialogues about the future of the community. Through this approach, they have gotten entire communities involved in grassroots ocean management. Since COBI started working with fishermen in the Yucatán, they have seen a 250 percent increase in lobsters and a 130 percent increase in other commercial species. "We are working closely with CONAPESCA on basic things," he says. "Besides saving the goddamn species, let's build trust."

Torre can barely contain his frustration as he thinks back on the vaquita debacle. He says that despite the efforts of the best minds in Mexico and the U.S., scientists just kept having the same arguments—on enforcement, on gill nets, on the Colorado River. Their locking into their own positions and those of their agencies, instead of cooperating, was devastating.

Waffles now runs an organization called Northeast Sustainable that builds conservation strategies from the ground up in the La Paz region of Baja, 550 miles south of Santa Clara. A few years ago the group approached a fishing community that was poaching fish from a nearby island reserve and offered an alternative. Together with the fishermen, it rejuvenated a long-dead estuary just a few miles away from the biggest city in the area to support clams. Rather than paying the locals not to fish, the organization paid them to manage the resource, doing biological surveys, releasing clams and guarding the beds from poachers. Today the fishermen manage a sustainable clam farm worth millions of dollars. They will have their first harvest this summer.

Driving around La Paz, Waffles expresses sadness that the same transformation could not help the vaquita. Later, sitting in a restaurant overlooking the ocean there, he says, "I truly believe that the only solution for the vaquita comes if the fishermen have the will to save it." Waffles points out that no community in history has undergone radical change to please a government or a group of foreign do-gooders. Whether you like the fishermen in an area or loathe them, he says, they are the only ones who can save a given species. In the upper Gulf, they are locked in a never-ending cycle of blame and combat. But fishing communities anywhere will undergo profound change to create a future for themselves and their families.

One of the five vaquitas found dead this past spring had been repeatedly stabbed, presumably by someone trying to hide it from officials or just out of pure rage. In contrast, down in La Paz, Waffles tells me about a recent conversation he had with the daughter of a poacher turned clam farmer:

"What does your father do for a living?" he asked her.

She responded, "My father is a restoration expert, an aquaculturist … and a fisherman." SA

MORE TO EXPLORE

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FROM OUR ARCHIVES

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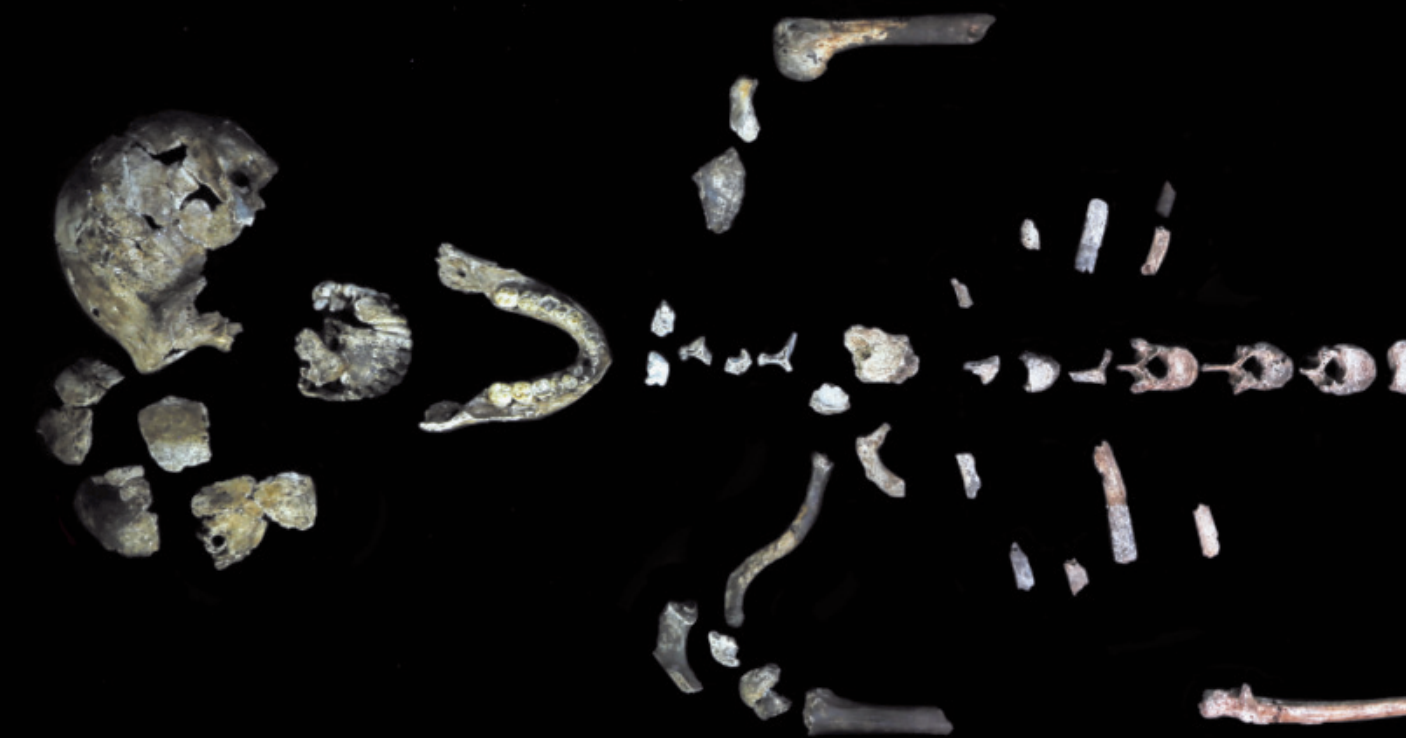
PALEOANTHROPOLOGY

Our Cousin



SUM OF ITS PARTS: Reconstruction of the pieces of Neo's skull reveals the visage of *Homo naledi*. To read more about the new discoveries, visit www.ScientificAmerican.com/neo

Neo

A remarkably complete skeleton and, at last, an age for mysterious *Homo naledi*

By Kate Wong

IN 2015 LEE BERGER of the University of the Witwatersrand, Johannesburg, and his colleagues caused a sensation when they unveiled more than 1,500 human fossils representing some 15 individuals, male and female, young and old, discovered in South Africa. It was one of the richest assemblages of human fossils ever found, recovered from a chamber deep inside an underground cave system near Johannesburg called Rising Star. The team deduced that the bones belonged to a new species, *Homo naledi,* which had a curious mix of primitive traits, such as a tiny brain, and modern features, including long legs. The scientists determined it was a capable climber and long-distance walker and surmised that it had disposed of its dead in the pitch-dark, hard-to-reach chamber.

Yet for all that the researchers were able to glean from the bones, the discovery was perhaps best known for what they could not ascertain: its age.

That eagerly awaited piece of the puzzle has finally fallen into place. In papers published online May 9 in eLife, the team reports it has dated the remains of *H. naledi* to between 236,000 and 335,000 years old—surprisingly young for a species with such a small brain. The researchers also announced the discovery of yet more fossils of *H. naledi* in a second chamber in Rising Star, including a skeleton of an adult male they nicknamed Neo, "gift" in the local Sesotho language.

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The findings raise intriguing questions about the origin and evolution of our genus, *Homo.* Despite the young age of the bones, the scientists maintain that *H. naledi*'s primitive features link it to much earlier members of the human family, and they argue that this species might even be a direct ancestor of *Homo sapiens.*

Berger and his collaborators also note that the new dates for *H. naledi* indicate it lived at a time when human ancestors were making sophisticated stone tools in the Middle Stone Age tradition. Many of the sites where archaeologists have discovered these tools do not contain any human fossils. Experts have typically assumed that large-brained humans made the implements. But if *H. naledi* was around at that time, as the authors suggest, it cannot be excluded as the toolmaker. In that case, scientists will need to reconsider the enduring notion that brain size drives complexity of behavior. Paleoanthropologist Mark Collard of Simon Fraser University in British Columbia, who was not involved in the new work, thinks there is good reason to do so: "The history of paleoanthropology is littered with deeply rooted assumptions that have been overturned by new discoveries." SA

JOHN HAWKS University of the Witwatersrand, Johannesburg

A MATTER OF CHOICE

Studies show that school vouchers lead to lower math and reading scores. So why has the Trump administration embraced them?

By Peg Tyre

IN BRIEF

The concept of vouchers originated with economist Milton Friedman. In 1955 he argued that the government should not run schools but instead offer parents educational stipends.

Vouchers are the centerpiece of the Department of Education's school reform plan. Until now, Washington, D.C., has been home to the only federally funded voucher program in the U.S.

A handful of other cities and states have experimented with small programs. Studies have found mixed to negative results in reading and math but higher high school graduation rates.

Illustration by Chris Gash

Peg Tyre, a former senior writer at *Newsweek,* contributes to *Politico* and the *Atlantic,* where she was a National Magazine Award finalist for her coverage of education. Tyre is a visiting scholar at the McCourt School of Public Policy at Georgetown University and is director of strategy at the Edwin Gould Foundation, which houses the EGF Accelerator, the U.S.'s premier incubator for education nonprofits.

In a 1955 essay, free market visionary Milton Friedman proposed a revolutionary model of education. Rather than seeing public schools as a rich local resource and driver of social mobility, he suggested they were a reflection of government overreach. Because a stable and democratic society depends on an educated electorate, he reasoned, the government should pay for children to go to school. But that did not mean the government should *run* schools. Instead, Friedman said, it ought to require a minimum level of education. And to finance that education, it should give parents "vouchers redeemable for a specified maximum sum per child per year if spent on 'approved' educational services." Breaking the government monopoly on education, he argued, would allow "consumers" (parents) to support the best "product"—that is, to enroll their kids in the most effective and highest-performing institutions. Mediocre public schools, subjected to market forces, would improve or perish.

The idea captured the imagination of elected officials and policy makers all over the world. Now President Donald Trump's secretary of education, Betsy DeVos, is preparing to give the scheme its first national rollout in the U.S. She has made voucher programs the centerpiece of her efforts to enhance educational outcomes for students, saying they offer parents freedom to select institutions outside their designated school zone. "The secretary believes that when we put the focus on students, and not buildings or artificially constructed boundaries, we will be on the right path to ensuring every child has access to the education that fits their unique needs," says U.S. Department of Education spokesperson Elizabeth Hill.

Because the Trump administration has championed vouchers as an innovative way to improve education in the U.S., Scientific American examined the scientific research on voucher programs to find out what the evidence says about Friedman's idea. To be sure, educational outcomes are a devilishly difficult thing to measure with rigor. But by and large, studies have found that vouchers have mixed to negative academic outcomes and, when adopted widely, can exacerbate income inequity. On the positive side, there is some evidence that students who use vouchers are more likely to graduate high school and to perceive their schools as safe.

DeVos's proposal marks a profound change of direction for American education policy. In 2002, under President George W. Bush's No Child Left Behind Act, the federal education mantra was "what gets tested, gets taught," and the nation's public schools became focused on shaping their curriculum around state standards in reading and math. Schools where students struggled to perform at grade level in those subjects were publicly dubbed "failing schools." Some were sanctioned. Others were closed. During those years, networks of privately operated, publicly funded charter schools, many of them with a curriculum that was rigorously shaped around state standards, opened, and about 20 percent of them flourished, giving parents in some low-income communities options about where to enroll their child. While charter schools got much of the media attention, small voucher programs were being piloted in Washington, D.C., and bigger programs were launched in Indiana, Wisconsin, Louisiana and Ohio.

Most school voucher programs were, at least originally, launched to help some of the most disadvantaged students. They target kids in poor urban communities with a high concentration of African-American and Latino children who would otherwise attend local public schools that have failed to show appropriate academic progress. The design of voucher programs varies from city to city and state to state, but in general, families are eligible to enroll in the voucher program if their local public school is troubled and if their child has been accepted into a private or parochial program. Those families then enroll in the voucher programs and are given a "scholarship"—usually in the $4,000 to $5,000 range—to defray (but typically not entirely cover) the cost of private tuition. In some programs, money comes from funds allocated for public education in the state coffers. Other programs depend on tax credits that allow individuals and corporations to make donations to a voucher fund or families to deduct some of the cost of private or parochial tuition and pay fewer annual state taxes.

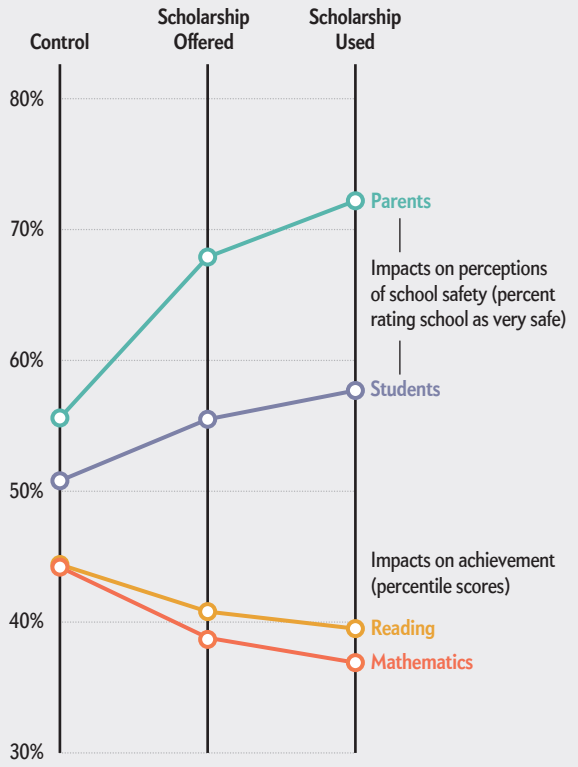
A MIXED PICTURE

Until now, only a handful of American cities and states have experimented with voucher programs. Around 500,000 of the country's 56 million schoolchildren use voucher-type programs to attend private or parochial schools. The results have been spotty. In the 1990s studies of small voucher programs in New York City, Washington, D.C., and Dayton, Ohio, found no demonstrable academic improvement among children using vouchers and high rates of churn—many students who used vouchers dropped out or transferred schools, making evaluation impossible. One

Ups and Downs

A recent study of Washington, D.C.'s federally funded voucher program found that math and reading scores among students who used vouchers declined, although the decline in reading scores was not statistically significant.

Voucher program had a negative impact on test scores but a positive impact on perception of school safety



SOURCE: *EVALUATION OF THE DC OPPORTUNITY SCHOLARSHIP PROGRAM: IMPACTS AFTER ONE YEAR.* MARK DYNARSKI ET AL. U.S. DEPARTMENT OF EDUCATION, APRIL 2017

study of 2,642 students in New York City who attended Catholic schools in the 1990s under a voucher plan saw an uptick in African-American students who graduated and enrolled in college but no such increases among Hispanic students.

In 2004 researchers began studying students in a larger, more sustained voucher plan that had just been launched in Washington, D.C. This is the country's first and so far only federally sponsored voucher program. There 2,300 students were offered scholarships, and 1,700 students used those scholarships mostly to attend area Catholic schools. The analysts compared academic data on those who did and did not opt for parochial school and found that voucher users showed no significant reading or math gains over those who remained in public school. But graduation rates for voucher students were higher—82 percent compared with 70 percent for the control group, as reported by parents. A new one-year study of the Washington, D.C., program published in April showed that voucher students actually did worse in math and reading than students who applied for vouchers through a citywide lottery but did not receive them. Math scores among students who used vouchers were around 7 percentage points lower than among students who did not use vouchers. Reading scores for voucher students were 4.9 percentage points lower. The study authors hypothesized that the negative outcomes may be partly related to the fact that public schools offer more hours of instruction in reading and math than private schools, many of which cover a wider diversity of subjects such as art and foreign languages.

Evaluations of some of the largest voucher programs—in Indiana (34,000 students) and in Louisiana (8,000 students)—also show negative outcomes. A four-year study of a sample of the 28,000-student voucher program in Milwaukee, which has a troubled public school system, found that for three years, between 2006 and 2009, there was no significant difference in academic gains between students who used vouchers to attend private schools and those who remained in traditional public schools. In the 2010–2011 school year, the voucher students made larger gains in reading and math—that same year the state legislature demanded that voucher kids be given state tests and that the scores be made public. Experts suggest that the threat of publicly revealing test scores caused private schools to create curriculums that conformed to state standards.

In a 2016 study of Ohio's Educational Choice (EdChoice) Scholarship program, which has used public money to supplement the tuition of 18,000 students at private and parochial schools, researchers used longitudinal data from 2003 through 2013 to examine academic outcomes of students who used vouchers and those who were eligible but did not transfer to a private school. (Because the Ohio voucher program requires children who use taxpayer money to take state tests, apples-to-apples scores were readily available.) They found that when children transferred out of their public schools through the program, their math scores—and to a lesser extent, their reading scores—dropped significantly and stayed depressed. "I was surprised by the negative—it's a big negative," says study co-author David Figlio of Northwestern University. He speculates that the negative outcome might have occurred because top private schools opted out of the voucher program because they did not wish to make students take state tests. As a result, voucher students were left with mostly subpar options. "A lot of the reason that parents are interested in sending kids to private schools is that there is too much testing in public," he says.

Better-performing students were the ones who used the voucher program, the study found. Interestingly, students who were left in Ohio public schools actually did better on standardized tests once the voucher program got under way, suggesting that public schools might have responded to the increased "competition" by teaching a curriculum aligned to the standards to be tested—or by doubling down on test preparation.

Ty Vinson, a mother of three from Columbus, Ohio, enrolled her children in a local Christian school using the EdChoice program. But after their test scores dropped, she switched them out. Vinson says she worried that her third, sixth and eighth graders, who earned straight A's at their new school, were not challenged enough.

Still, she appreciated the experience. "They got to be involved

Graphics by Tiffany Farrant-Gonzalez

in activities like science fairs and poetry contests. They do offer art, music, science and all the different areas of the curriculum, some of which are not offered so much in the public schools," she notes. But she decided to move her children back to the online charter school they were attending before. Vinson has not considered public school, she says, because her family is black, and she perceives too many racial issues in the local schools.

VOUCHER SYSTEM IN CHILE

OTHER COUNTRIES, namely Sweden, the Netherlands, New Zealand and Colombia, have experimented with voucher programs, also with mixed results. But no country embraced the scheme as wholeheartedly as Chile, which implemented a universal voucher program in the 1980s under dictator Augusto Pinochet. Before the reform, three types of schools existed in Chile: public (accounting for 80 percent of the enrollment), subsidized private (14 percent)—largely Catholic schools—and fee-paying private for the elite (6 percent). In 1981 the system was decentralized, and parents could enroll their children in public municipal schools, subsidized private schools that accepted vouchers, and nonsubsidized private schools, which charged about five times the amount of the government subsidy and were thus available only to the elite. Middle-class families stampeded out of public schools. By 2002 private voucher schools reached 38 percent of enrollments, at the expense of the public sector, which dropped to 53 percent. By 2004 private voucher enrollment had reached 41 percent. Poor families, many of whom were unable to gain admission to private schools or lived in rural areas without private schools, stayed in the public system. By 2006, 42 percent of students in the lowest income quintile of the population, 28 percent of students from the second-lowest quintile and 4 percent from the wealthiest quintile attended public schools.

In the early 2000s Alejandra Mizala, an economist at the University of Chile, and Florencia Torche, a sociologist now at Stanford University, launched a comprehensive study of fourth and eighth grade students in public and private voucher schools in Chile using census data and information about parental education and income. In a paper published in 2012 in the *International Journal of Educational Development,* the researchers found that enrollment in private voucher schools created a hierarchy, with private school students segregating themselves by income. "A much larger proportion of the variance in socioeconomic status is *between schools* in the private-voucher sector than in the public one," the study authors wrote. "This pattern suggests that while the private-voucher *sector* serves an economically diverse population, each voucher *school* focuses on a socioeconomically homogeneous community."

In other words, economic stratification in Chile increased under vouchers by the type of school and by actual school community. Although there are no good studies that track socioeconomic stratification through vouchers in the U.S., research conducted by Halley Potter, a senior fellow at the progressive Century Foundation, has shown that voucher programs tend to exacerbate racial segregation in both public and private schools. Further, she found that more highly educated parents, often a proxy for families with a higher income, are more likely to use vouchers to transfer their children to private schools.

SAFETY VS. ACHIEVEMENT

IN THE FACE of such mixed results, what is motoring voucher programs forward? A few studies, including an early look at the federally funded Washington, D.C., program, have shown that vouch-

What Makes a Good School?

It is a question experts have debated at least since Socrates developed his famous instructional method. In the past several years researchers have homed in on factors that predict high academic achievement in K–12 schools. Unfortunately, in the U.S., those components still cluster in institutions that serve students from high socioeconomic backgrounds—an imbalance that Secretary of Education Betsy DeVos says vouchers can address. Here are some of the constants that good schools share, according to studies.

A carefully sequenced curriculum that provides broad content knowledge in English, math, science, history, art and music. For many years researchers did not understand the power of content knowledge to improve skills such as reading comprehension and critical thinking. Lately neuroscientists—and some high-performing district and charter schools—have begun focusing on the importance of building factual knowledge in children, especially those from low-income families. Yet it is important that content be taught in an engaging way and not through rote memorization.

Math introduced in the earliest grades and taught by a content expert. If a content expert is not available, then the teacher should at least take real joy in math instruction. Math phobia is highly contagious and difficult to cure.

Daily physical activity. As the focus on testing grew more intense, PE dropped out of school schedules. But science suggests that all kids should get 60 minutes of moderate aerobic exercise every day to be at their cognitive best.

Safety. In 1908 Arthur C. Perry, principal of a Brooklyn high school, published *The Management of a City School,* describing how school climate affects learning. Since then, researchers who study cognition have mostly agreed with his theories—more learning takes place in classrooms with fewer disruptions.

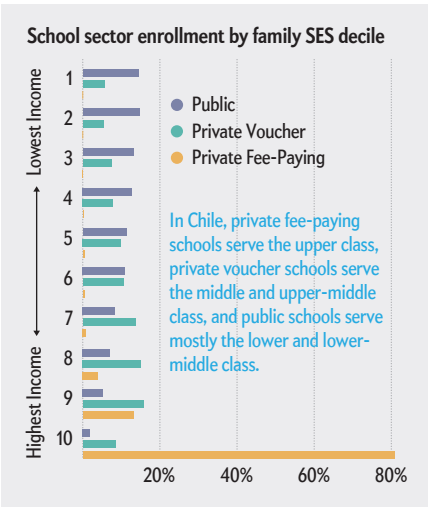
Experienced teachers. Recent studies suggest that teachers continue to gain mastery in instruction (as measured by student test scores) and student engagement (as measured by absenteeism) throughout their first 10 years in the classroom.

—P.T.

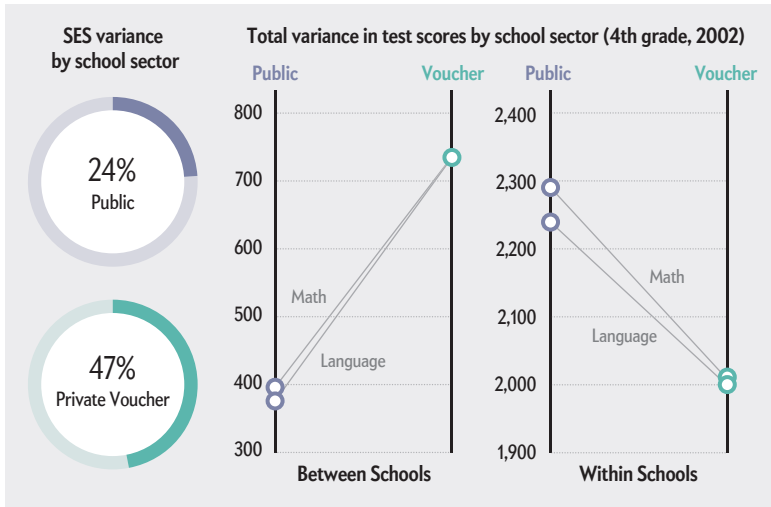
Chile's Bold Experiment

Perhaps no country has embraced vouchers as wholeheartedly as Chile, which implemented a universal voucher program in 1981. A 2012 study found that the system had led to profound stratification by income, with the highest achievements occurring in the wealthiest schools. Since then, Chile has instituted reforms aimed at bringing greater equality. Among the changes: providing higher subsidies for vouchers for lower-income students and prohibiting elementary voucher schools from accepting students based on parental interviews.

The Chilean educational system displays profound stratification in socioeconomic status (SES) …



… with the greatest income and test-score disparities occurring among schools that accept vouchers. Within voucher schools, student SES and academic achievement are relatively homogeneous.



SOURCE: "BRINGING THE SCHOOLS BACK IN: THE STRATIFICATION OF EDUCATIONAL ACHIEVEMENT IN THE CHILEAN VOUCHER SYSTEM," BY ALEJANDRA MIZALA AND FLORENCIA TORCHE, IN *INTERNATIONAL JOURNAL OF EDUCATIONAL DEVELOPMENT*, VOL. 32, NO. 1; JANUARY 2012

ers can boost high school graduation and college matriculation rates. Advocates say those measures are more important than achievement on state tests. "We should care about education attainment: how long they stay in the system and degrees they obtain. That is more predictive of life outcomes," says Patrick Wolf, co-author of *The School Choice Journey* and education professor at the University of Arkansas. But such sentiments are at odds with how we have long demanded our public schools operate. For two decades policy makers have harshly criticized public schools for social promotion—the practice of moving a child to the next grade level regardless of academic achievement. The merit of public schools was determined solely on the number of students achieving mastery of state standards, as indicated by standardized scores.

Reading and math scores may also not be the most important consideration for parents. The April study of Washington, D.C.'s voucher program found that parents of children who used vouchers were more likely to rate their child's school as very safe, for example. Some religiously affiliated parents may also perceive more value in a school's culture than in standardized test results. "If I'm a deeply religious person, I might choose an education where my children are raised according to my religious values and culture," says Robert Pondiscio, a senior fellow at Thomas B. Fordham Institute, a right-leaning think tank in Washington, D.C. "I have a view of my child's education that is more than test scores. Other factors may weigh more heavily."

But other experts worry that vouchers too often shuffle students from one failing system of schools to another. Northwestern's Figlio suggests creating a team of inspectors to conduct top-to-bottom reviews of schools that take vouchers. "There are truly terrible schools in terms of literacy and numeracy," he says. "We can't just let the market run and assume people will be in good schools. There should be some allowance for accountability." That takes us back to the question of who should decide which schools are "good" and how.

Voucher proponents say parents, even those using tax dollars to pay tuition, should be able to use whatever criteria for school choice they see fit. A provocative idea, but if past evidence can predict future outcomes, expanding voucher programs seems unlikely to help U.S. schoolchildren keep pace with a technologically advancing world. SA

MORE TO EXPLORE

Evaluation of Ohio's EdChoice Scholarship Program: Selection, Competition, and Performance Effects. David Figlio and Krzysztof Karbownik. Thomas B. Fordham Institute, July 2016. https://edex.s3-us-west-2.amazonaws.com/publication/pdfs/FORDHAM%20Ed%20Choice%20Evaluation%20Report_online%20edition.pdf

State-by-state comparisons of school voucher laws by the National Conference of State Legislatures: www.ncsl.org/research/education/voucher-law-comparison.aspx

FROM OUR ARCHIVES

Brain Science in the Classroom. Daniel T. Willingham; Forum, September 2012.

scientificamerican.com/magazine/sa

DIAMOND RING effect just before and after totality shows light from the solar photosphere shining through a valley on the moon.

ASTROPHYSICS

The first total solar eclipse to cross the U.S. from coast to coast in

99 years is not only a must-see spectacle but also a valuable scientific opportunity

By Jay M. Pasachoff

THE GREAT SOLAR ECLIPSE *of 2017*

Jay M. Pasachoff is an astronomer at Williams College. He is chair of the Working Group on Solar Eclipses of the International Astronomical Union. His work is funded by the National Geographic Society and the National Science Foundation.

I love to be outdoors during solar eclipses, enjoying the universe appearing to darken around me while my research observations get under way. Long ago I used to suggest that people make a pinhole projector or even use cheese graters from their kitchens to watch these events. But in recent years the availability of partial-eclipse filters for only a dollar or so has made such advice obsolete. Now anyone can glance up at the sun through such a filter starting more than an hour prior to totality and see an apparent bite being taken out of the solar disk. During the last few minutes before totality, you will notice that the ambient light changes in quality, becoming eerie. Shadows sharpen because they result from a thin crescent of sunlight rather than the full disk of the sun. The air cools, and a wind stirs. Shadow bands may sweep rapidly over the ground.

With seconds to go, as the moon moves completely in front of the sun, just a few shafts of sunlight leak through valleys on the moon's edge, reducing the sun to an arc of bright beads. These fade out until only one is left—so bright that it looks like the diamond on a ring, perhaps with a narrow, reddish rim to its sides and a whitish band all around the lunar silhouette. Then the diamond, too, disappears. You can and should drop your filters and look straight at what is left of the sun, a region of its atmosphere that had been hidden by the blue sky.

This is the inner and middle solar corona, the plume of plasma that flies out from the sun's surface. It is about as bright as the full moon—a million times as faint as the everyday sun—and equally safe to look at with the naked eye. You first glimpse the corona as the band of the diamond ring, and then you see it in all its glory: a pearly white halo of gas that extends outward to several times the sun's radius. If you are lucky, you might see a mighty eruption of plasma into interplanetary space.

But what, really, is the point of my trying to describe a total solar eclipse in words? It is so astonishingly moving and beautiful that nobody has ever described it adequately. People routinely come up to me after eclipses to say that they know how I had tried to convey the excitement but that I had nonetheless fallen short. Television and computer screens do not do it justice. Photographs flatten the dynamic range and lose the dazzling contrast. To be outdoors as the universe apparently darkens, gradually at first and then by an additional factor of 10,000 within seconds, is completely discombobulating. It conjures up primal fears of the sun being taken away.

I saw my first eclipse as a first-year college student, and I was hooked. Starting then, I have been all over the world to see 65 solar eclipses (including 33 total eclipses). I look forward to my 66th on August 21, when the path of totality traverses from the U.S. West Coast to the East Coast for the first time since 1918.

And I do not catch these events just for the fun of it—eclipses offer scientists viewing conditions that routine observations cannot replicate. Although terrestrial telescopes can be equipped with a small metal cone or disk—making a so-called coronagraph—to blot out the sun on demand, their artificial eclipses are not as good as the real ones. The ambient air molecules leave the sky too blue and bright, even from pristine and high mountain sites. And space coronagraphs have to blot out not only the everyday solar disk but also a wide band around it, or else too much light would scatter inside the instrument. Furthermore, any telescope has a limited resolution and smears out incoming light a bit. Natural eclipses do not have this problem, because the "telescope" is, in effect, the entire Earth-moon system, with an exceptionally high resolution. We link our ground-based observations with spacecraft views to get a complete picture of the sun. Only in the crisp shadow of the moon are we able to see the inner and middle part of the corona in visible light.

It is in those inner expanses that we seek an answer to one of the most nagging puzzles in astrophysics: Why does the sun's temperature increase as you move away from its surface? Usually things cool down as you retreat from a hot object, such as a campfire or a steam radiator. Within the sun, the temperature starts at

IN BRIEF

On August 21, Americans in a narrow path from Oregon to South Carolina will be treated to a total eclipse of the sun.

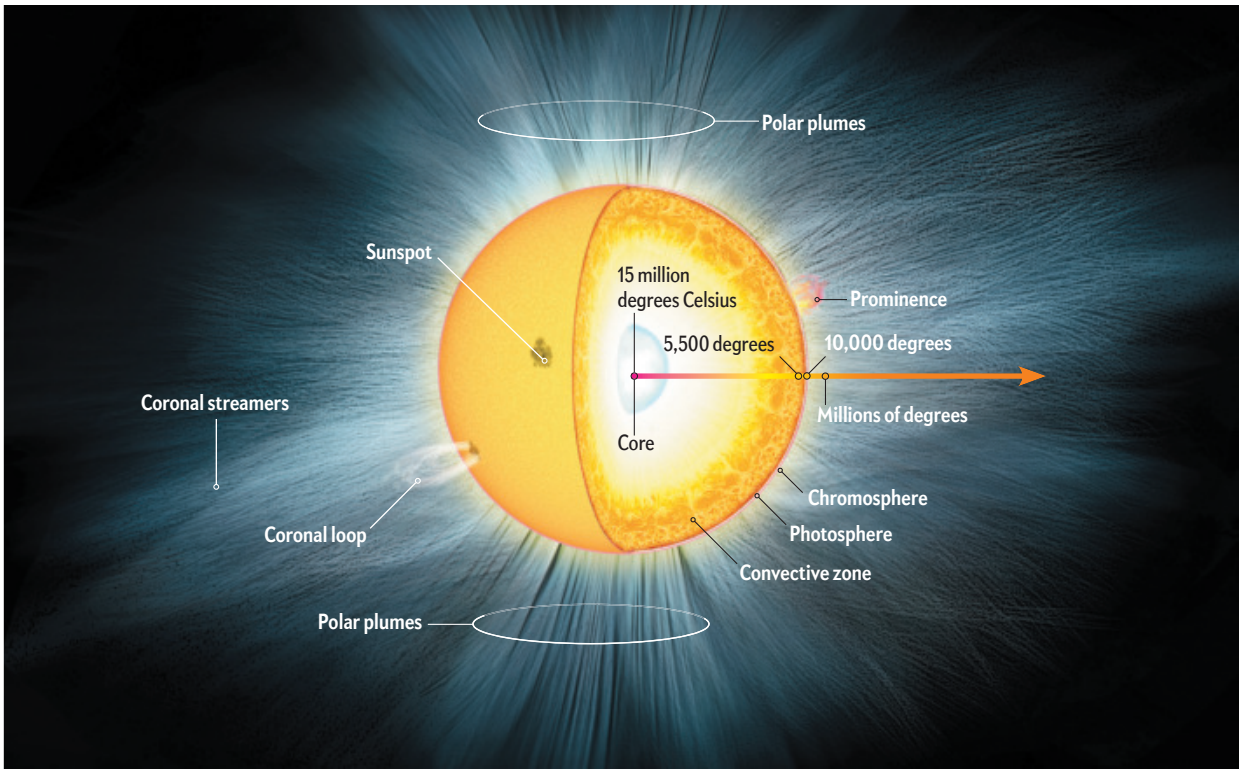
The eclipse offers a rare and precious opportunity to study the sun under conditions impossible at any other time.

Scientists will be seeking answers to lingering mysteries such as how the sun's magnetic field shapes the solar corona, why the corona is so hot, and more.

PRECEDING PAGES: JAY M. PASACHOFF *Getty Images*

The Shadowed Sun

Observing the sun during a solar eclipse, when its face is blocked by the moon's shadow, allows astronomers to study layers of the solar atmosphere that are otherwise impossible to image. The solar corona is a halo of gas that streams out from the sun's surface in plumes and loops. Eclipse observations could help solve the mystery of why the corona is hotter than the sun's surface.



Two Hypotheses: Flares or Waves

Scientists have proposed two general classes of ideas to explain where the solar corona gets its high temperature. By studying the corona during eclipses and measuring how quickly coronal gas oscillates, researchers hope to distinguish between the two ideas or perhaps determine that both processes take place.

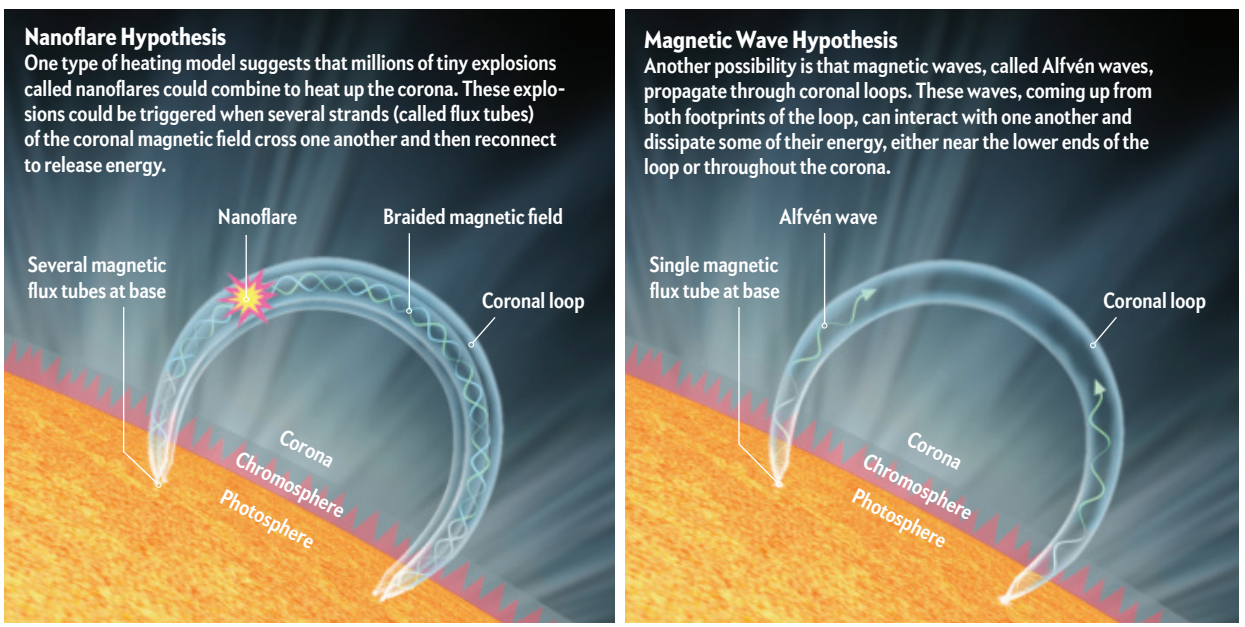
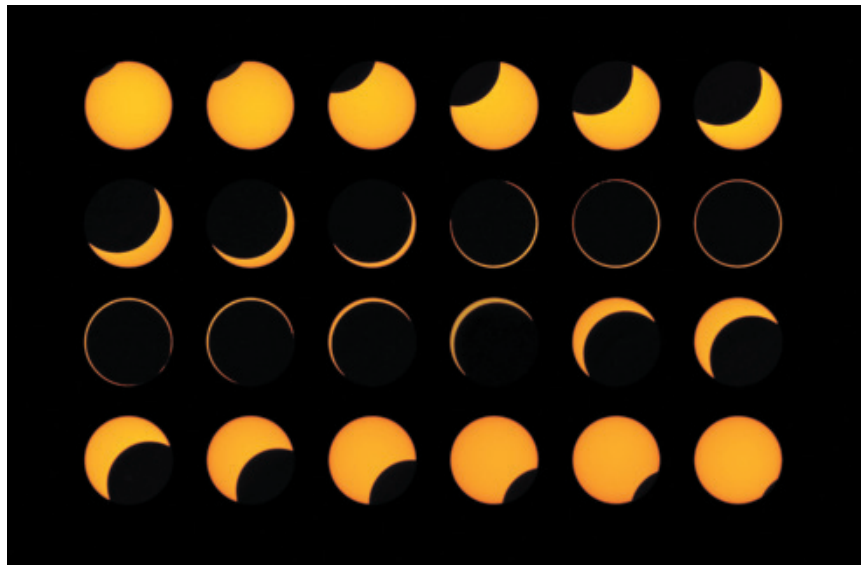


Illustration by Don Dixon

15 million degrees Celsius at the center and steadily falls as you move outward, dropping to 5,500 degrees C at the solar photosphere, the surface that emits sunlight into space. But then the trend reverses. The tenuous gas just above the visible surface climbs back up to over 10,000 degrees C and abruptly leaps to millions of degrees. Scientists still debate the details of how that occurs.

We have made tremendous observational and theoretical advances since I first described the science of the solar corona in *Scientific American* in 1973. A flotilla of spacecraft now monitor the sun in ultraviolet light and x-rays, which we cannot view from the ground, and researchers have developed sophisticated tools to link all our observations together. We know the outline of the solution of the coronal-heating problem—that it involves the sun's magnetic field—but the details remain murky. And this is hardly the only problem that the corona presents to us. Observations during the upcoming eclipse should help tackle these questions.



SEQUENCE from the annular solar eclipse of February 2017, as photographed by the author in the Patagonia region in Argentina.

THE SOLAR LANDSCAPE

SCIENTISTS ALREADY UNDERSTAND much about the solar corona. For one thing, it looks like a giant porcupine. It is drawn into fine streamers, some of which are wider at their base and come to a peak at higher altitudes, like pointy helmets. The shape they form varies with the sunspot cycle.

When spots proliferate, as in the years 2012 through 2014, streamers burst out even from latitudes as high as 30 degrees north and south so that the corona appears round overall. During sunspot minimum periods, such as the one we are in, the corona is squat, and the streamers we see are limited to regions nearer the sun's equator, and thin, straight coronal plumes appear at the poles. From the open regions between streamers, a flow of charged particles called the solar wind escapes outward into the solar system at hundreds of kilometers per second, perhaps twice the rate of the solar wind from other regions. At the base of the corona, anchored to the solar photosphere, are small loops of gas, perhaps made up of multiple threads too fine for our current observations to discern. These coronal loops may pulse as waves bounce back and forth along or through them.

All this delicate intricacy is the product of the solar magnetic field, which arises from churning gas deep within the sun. What researchers do not know, however, is exactly how the dynamics of the magnetic field are responsible for the bizarrely high temperature of the corona. We know the magnetic field is involved because magnetic processes are not subject to the same thermodynamic restrictions that prevent energy from flowing by heat conduction from the hot surface to the even hotter corona.

EXPLOSIONS OR WAVES?

SCIENTISTS HAVE TWO MAIN IDEAS for how the sun's magnetic field could transfer some of its energy into the corona to heat it up. One way is through extremely tiny solar flares. These explosions occur when the magnetic field undergoes an abrupt change in its configuration, within seconds. When you map out the field at the sun's surface, you occasionally see the north and south polarities in sunspot regions become jumbled. This condition puts the magnetic field under enormous stress, and to relieve it, the two polarities suddenly connect in a new way, emitting tremendous amounts of stored energy. Such a reconnection heats the corona locally to 10 million degrees C or higher, gives off a bright flash, and sometimes ejects plasma into space. The flare can zap spacecraft orbiting Earth and could pose a serious risk to astronauts journeying to Mars.

The flares we observe are too intermittent to explain the baseline temperature of the solar atmosphere, but might explosions too small to detect individually also wrack the corona? James Klimchuk of NASA's Goddard Space Flight Center has especially championed the idea of such nanoflares. Millions of small explosions going off in the corona every second, each with a billionth as much energy as a large flare, would keep it broiling hot.

The main competing set of theories is that oscillations in the magnetic field heat the corona. Vibrating loops in the lower corona could shake the surrounding gas, thereby raising its temperature. These waves could take multiple forms. Scientists have ruled out sound waves, driven by gas pressure, but Alfvén waves, driven by magnetism or by a hybrid of the two, called magnetoacoustic waves, are still viable. Could magnetic waves of some kind be enough to raise the coronal temperature to millions of degrees?

In principle, researchers should be able to distinguish between the nanoflare and wave mechanisms by measuring oscillations of coronal gas. Fluctuations with periods from about 10 seconds to minutes would betray the passage of standard Alfvén waves along coronal loops. Observations of vibrations of the sun's surface using a technique known as helioseismology suggest that the sun is capable of triggering such waves. Although its strongest oscillations occur with a comparatively languid

JAY M. PASACHOFF (*photographs*); CHRISTIAN LOCKWOOD *Williams College* (*composite*)

period of about five minutes, those are only one type among many undulations that the surface undergoes.

Eclipse observations could be crucial to measuring fluctuations in coronal loops. The logistic advantages of observing from Earth allow us to use equipment that has higher temporal resolution than exists on any current spacecraft. My team uses rapid-readout charge-coupled devices (CCDs) that capture images numerous times a second. By comparison, the Atmospheric Imaging Assembly cameras on NASA's Solar Dynamics Observatory (SDO) have been taking observations through several of their range of 10 filters every 12 seconds, and the Solar Ultraviolet Imager on the National Oceanic and Atmospheric Administration's new Geostationary Operational Environmental Satellite (GOES-16) has a 10-second cadence at best for its six filters.

What we have found so far extends the realm of possibilities. Some oscillations may have periods shorter than one second, matching a theoretical prediction of a special mode of Alfvén waves that travels along the surfaces of loops rather than through their interiors. But our data are scanty: only a few minutes of such high-cadence observations from a pair of prior total solar eclipses. This year we will be using our complicated CCD apparatus, with filters of astonishingly pure color, to isolate the hot coronal gas to search for the time spectrum of waves again. We hope that our results will help researchers choose between the different theories of coronal heating or even lead them to the conclusion that several mechanisms are at work simultaneously. In the active regions above sunspots, the conditions for flaring are auspicious, and waves are comparatively weak. In quiet regions, however, we may have either waves on small loops or trillions of nanoflares all the time.

Millions of small explosions going off in the corona every second, each with a billionth as much energy as a large flare, would keep it broiling hot.

ECLIPSE TACTICS

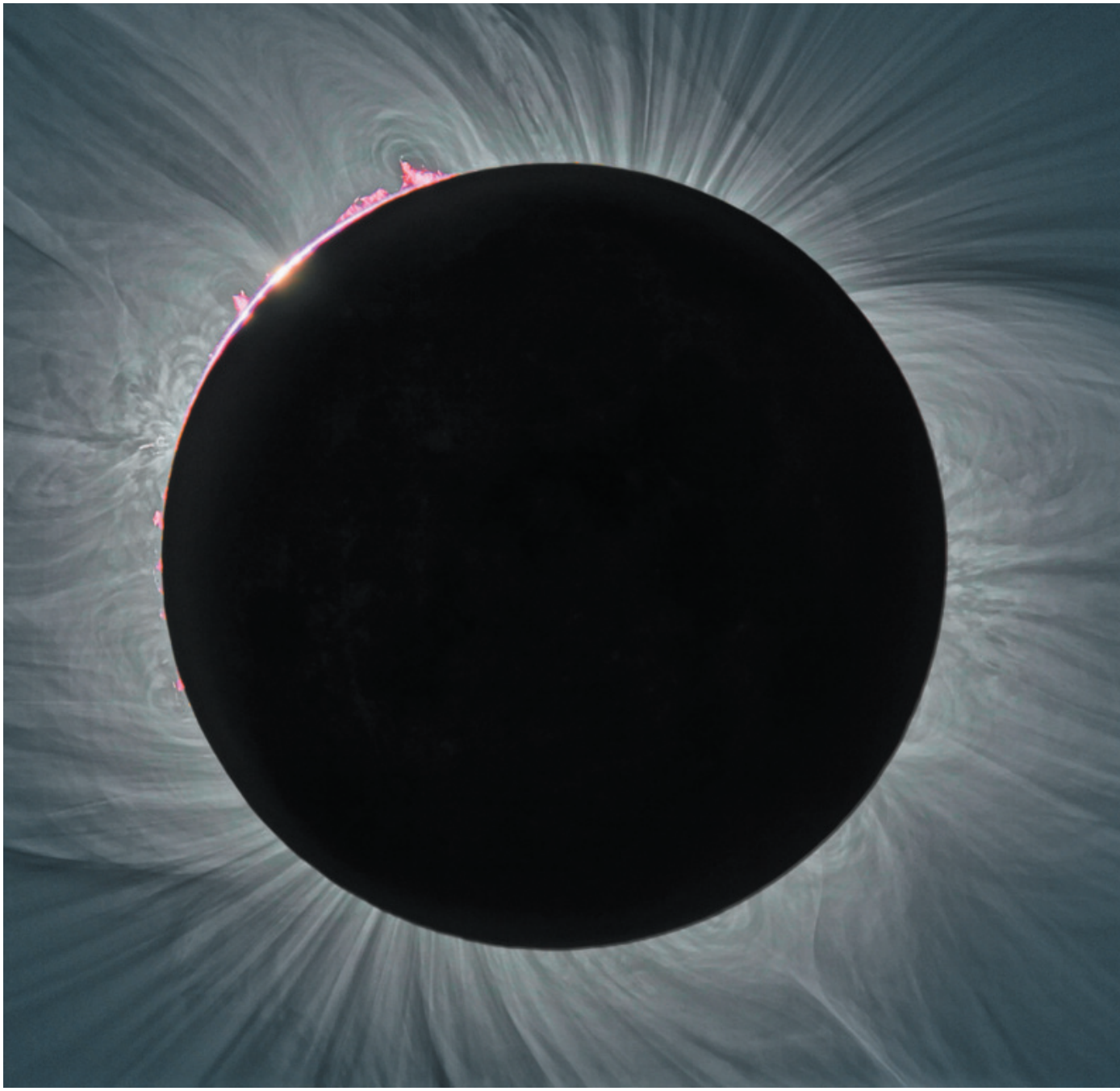
SCIENTISTS HAVE DEVISED SOME TRICKS for making the most of the exceptional opportunities eclipses offer. Eclipse observations enable us to scrutinize the shape of the corona in high spatial and temporal resolution. Our ground-based eclipse images show detail about eight times finer in each dimension than the best space coronagraph. Eclipses do have the downside of being brief and intermittent, but we compensate by melding data sets from separate eclipses and from different sites during a single eclipse.

For instance, by observing eclipses over the full 11-year solar-activity cycle, we follow changes in the degree of roundness of the corona, which reflects the distribution of streamers at various latitudes, and compare them with other measures of solar activity. I work with astronomer Vojtech Rušin of the Slovak Academy of Sciences on such studies. Although the corona is visible during an eclipse for only a few minutes from any given site, we can combine observations from multiple sites to ascertain changes in coronal streamers and plumes over the hours it takes the moon's shadow to traverse Earth. During the August 21 eclipse, we may even get continuous coast-to-coast observations with viewings from citizen scientists.

A further reason to combine multiple eclipse images is to capture the huge range of brightness in the corona. From individual images taken over many exposures, we can pick out the properly exposed pieces and merge a dozen of them at a time. The widely acknowledged expert in this computer-imaging work is Miloslav Druckmüller, a computer scientist at the Brno University of Technology in the Czech Republic. Given that the corona is about 1,000 times brighter just outside the edge of the sun than it is only one solar radius farther out, we must select the best-exposed parts from dozens of different images and assemble them. Using such composite images from past total eclipses—seen most recently in Indonesia, Svalbard, Gabon, Australia, and elsewhere—my team has measured velocities in coronal streamers, polar plumes, and mass ejections. We hope to add significantly to these observations in August.

Another trick is to exploit the gradual encroachment of the lunar silhouette during an eclipse. As sunspot regions are covered or uncovered by the edge of the moon, telescopes might see abrupt changes in the sun's brightness, allowing us to pinpoint details. To get the very highest spatial resolution this year, my team is collaborating with Dale Gary of the New Jersey Institute of Technology, Tim Bastian of the National Radio Astronomy Observatory and Tom Kuiper of NASA's Jet Propulsion Laboratory to use radio telescopes to measure changes in the radio radiation from whatever active sunspot regions may be visible at various frequencies as the moon covers the sun. Even though these telescopes are outside the path of totality, about 70 percent of the solar disk will still be covered by each of them. We will get the highest-resolution radio observations with the Expanded Owens Valley Solar Array in California, with its 13 linked radio telescopes that will take continuous observations of the sun at hundreds of frequencies from 2.5 to 18 gigahertz. Lower-resolution images from the Goldstone Apple Valley Radio Telescope, also in California, will improve image quality by filling in the background. We should be able to match the exact positions of brightening in coronal loops, as seen at these radio wavelengths, with the spots that glow in the ultraviolet or in x-rays from spacecraft, and thereby learn how the loops are heated.

The magnetic field of the photosphere is well studied, but that of the corona is much less so. To rectify that issue, Ed DeLuca of the Harvard-Smithsonian Center for Astrophysics and Harvard University graduate student Jenna Samra, working with solar scientists Leon Golub of the Harvard-Smithsonian Center and Philip Judge of the High Altitude Observatory at the National Center for Atmospheric Research (NCAR) in Boulder, Colo., plan



COMPOSITE of dozens of images taken during a total solar eclipse in Libya shows the chromosphere (*pink*) and corona.

MILOSLAV DRUCKMÜLLER AND PETER ANIOL *Getty Images*

to follow the eclipse from an NCAR Gulfstream V aircraft. From their perch above the bulk of the infrared-absorbing atmosphere, they will be able to measure the strength of infrared spectral lines, hoping to find ones that are magnetically sensitive.

If successful, they plan to fly again during a later eclipse with polarization filters added to measure the coronal magnetic field. By separating out light waves with different orientations, polarization measurements help us to identify the different components of the corona. The inner middle part of the corona that we see with our eyes during a total eclipse comes from highly ionized gas scattering ordinary sunlight toward us. This scattering polarizes the light, and the motion of electrons caused by this process smears out the dark lines that otherwise intrude in the sun's rainbow spectrum. Farther out in the corona, nearer the orbit of Mercury, dust in interplanetary space bounces light toward us but does not polarize it or wipe out the ordinary solar spectrum. Others preparing to study polarization at this year's eclipse include Nat Gopalswamy of NASA's Goddard Center, Judge and Steven Tomczyk, both at the High Altitude Observatory, and Padma Yanamandra-Fisher of the Space Science Institute. After

the Daniel K. Inouye Solar Telescope being built on Maui starts observing in 2018, one of its instruments should eventually be able to measure the coronal magnetic field directly by studying the polarization of infrared spectral lines. And when NASA's Parker Solar Probe launches in 2018, it will fly through the solar corona and help unravel the uncertainties in coronal heating.

WORLDWIDE EFFORT

ALL IN ALL, the observing effort during this eclipse will be truly enormous, and I have only scratched the surface here. NASA has funded 11 proposals, six for coronal studies and five related to the response of Earth's atmosphere to the dramatic eclipse cooling, a topic on which I have been working with Marcos Peñaloza-Murillo of the University of the Andes in Venezuela. Another major U.S. research group using eclipses to study the corona is led by Shadia Habbal of the University of Hawaii's Institute for Astronomy. Her team, which she calls the Solar Wind Sherpas, will image the corona through filters chosen to map plasmas of different temperatures. Habbal's new NASA grant supports the enhancement of the group's recently designed dual-channel imaging spectrograph, which was successfully tested in 2015. A variety of observations from the ground and from space will provide the most comprehensive study of the infrared corona, its spectrum and its polarization acquired to date.

My group has had the benefit of international collaborations during the 33 total solar eclipses that I have observed from sites around the world. Now it is time for us to repay the hospitality. We expect the high-quality imaging and analysis of Serge Koutchmy of the Institute of Astrophysics of Paris and his colleagues to contribute to the study of the August eclipse. At my own team's sites, we will be joined by our colleagues from Australia, Slovakia, Greece, Japan, China, Iran, and elsewhere.

Citizen scientists will also have plenty of opportunities to contribute to researchers' eclipse efforts. I am involved in the Eclipse Megamovie Project, which is based at the Space Sciences Laboratory at the University of California, Berkeley, and headed by Laura Peticolas. People will be able to send in images through a Google interface for archiving and assembly into continent-spanning movies, which will be available to citizen scientists for viewing and analysis. In a similar vein, Matt Penn of the National Solar Observatory has organized the Citizen Continental-America Telescopic Eclipse (Citizen CATE) Experiment, a continent-spanning collaboration of about 70 sites with identical small telescopes and CCD detectors.

One unusual experiment this August has nothing to do with the corona; indeed, the corona will get in our way. Arthur Eddington famously tested Einstein's general theory of relativity at an eclipse in 1919. He looked for signs that the sun's mass was bending the light of distant stars behind it, an effect that is actually caused by the relativistic warping of spacetime. I have spent decades telling people that we have better things to do at a total eclipse than repeat this experiment. After all, physicists have more precise ways to test relativity theory nowadays. But it turns out that new observing capabilities may make the investigation at this year's eclipse a useful one—or at least interesting.

Retired California physicist Don Bruns will carry out such observations. He has intricate plans for calibrating his telescope by measuring many nighttime star images. An earlier attempt to use observations taken with digital single-lens-reflex (DSLR) cameras at the 2006 eclipse by Jean-Luc Dighaye of Belgium—which Carlton Pennypacker of U.C. Berkeley and Lawrence Berkeley National Laboratory and I tried to help analyze—failed, but that was with the large pixels of commercial DSLRs. We hope that the smaller pixels and precise calibration of an astronomical CCD detector will succeed. Bradley Schaefer of Louisiana State University has argued that modern imagers have enough resolution and sensitivity to exceed the accuracy of past tests, and he will also try to observe the effect. Because of a just released catalog created by the European Space Agency's Gaia spacecraft, we now know the positions of stars with extremely high precision, so we could look for any deflection caused by the sun with fewer calibrations at the telescope.

NEARLY HERE

THE AUGUST 21 ECLIPSE will begin at sunrise in the Pacific Ocean. Totality hits the U.S. mainland in Oregon, with partial phases visible throughout the U.S., Canada and Mexico and farther south into South America. After leaving South Carolina near Charleston some 90 minutes later, the total eclipse will end at sunset over the Atlantic, with partial phases visible from northwestern Africa and western Europe.

Assuming the weather cooperates, scientists and the general public should be impressed and even overwhelmed. Combining ground-based eclipse results with the observations from satellites in the visible, ultraviolet, x-ray and radio parts of the spectrum will provide the most complete view of the solar atmosphere ever seen.

Whatever we conclude for the sun will also apply to the billions and trillions of stars like the sun that we cannot see in the same detail. Some might find it disconcerting that the sun, arguably the best studied of all celestial objects, is so incompletely understood. But I see the lingering questions as a wonderful excuse to share one of the greatest experiences in nature.

As for me, decades ago I was so busy photographing during totality that I barely had time to look up to see it. But now, with computer automation, I can enjoy a few seconds to savor the eclipse while cameras click away and electronic sensors upload their data to computers. I look forward to the view of my 66th solar eclipse from Oregon. Those who are as dazzled as I am can think ahead to the 2019 and 2020 eclipses in Chile and Argentina and the 2024 total solar eclipse that will sweep across the eastern U.S. from Texas to Maine. And a 2023 annular eclipse will show partial phases over North and South America. SA

MORE TO EXPLORE

Structure and Dynamics of the 2012 November 13/14 Eclipse White-Light Corona. J. M. Pasachoff et al. in *Astrophysical Journal,* Vol. 800, No. 2, Article No. 90; February 20, 2015.

Key Aspects of Coronal Heating. James A. Klimchuk in *Philosophical Transactions of the Royal Society A,* Vol. 373, No. 2042, Article No. 20140256; May 28, 2015.

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FROM OUR ARCHIVES

The Solar Corona. Jay M. Pasachoff; October 1973.

The Paradox of the Sun's Hot Corona. Bhola N. Dwivedi and Kenneth J. H. Phillips; June 2001.

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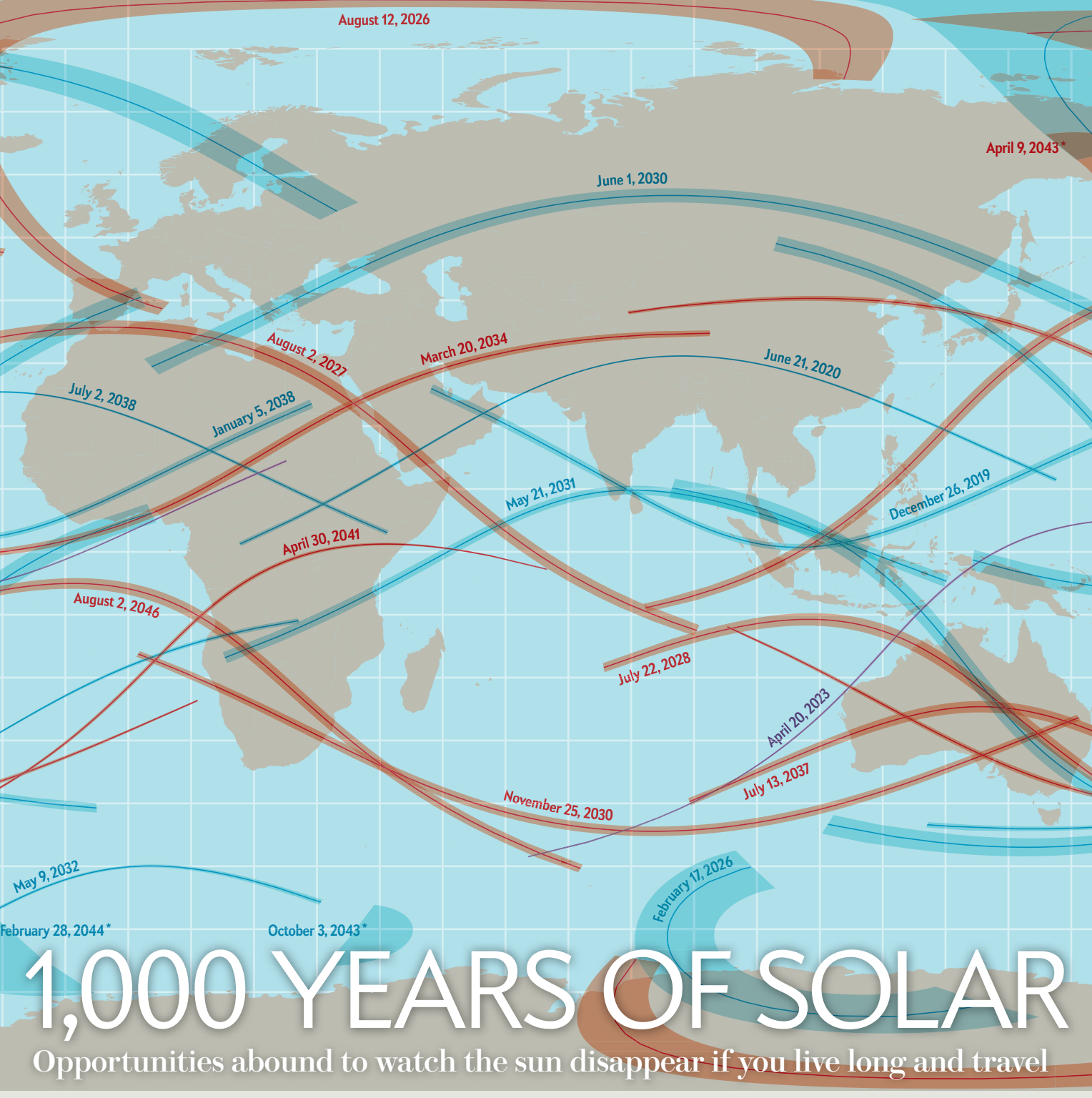


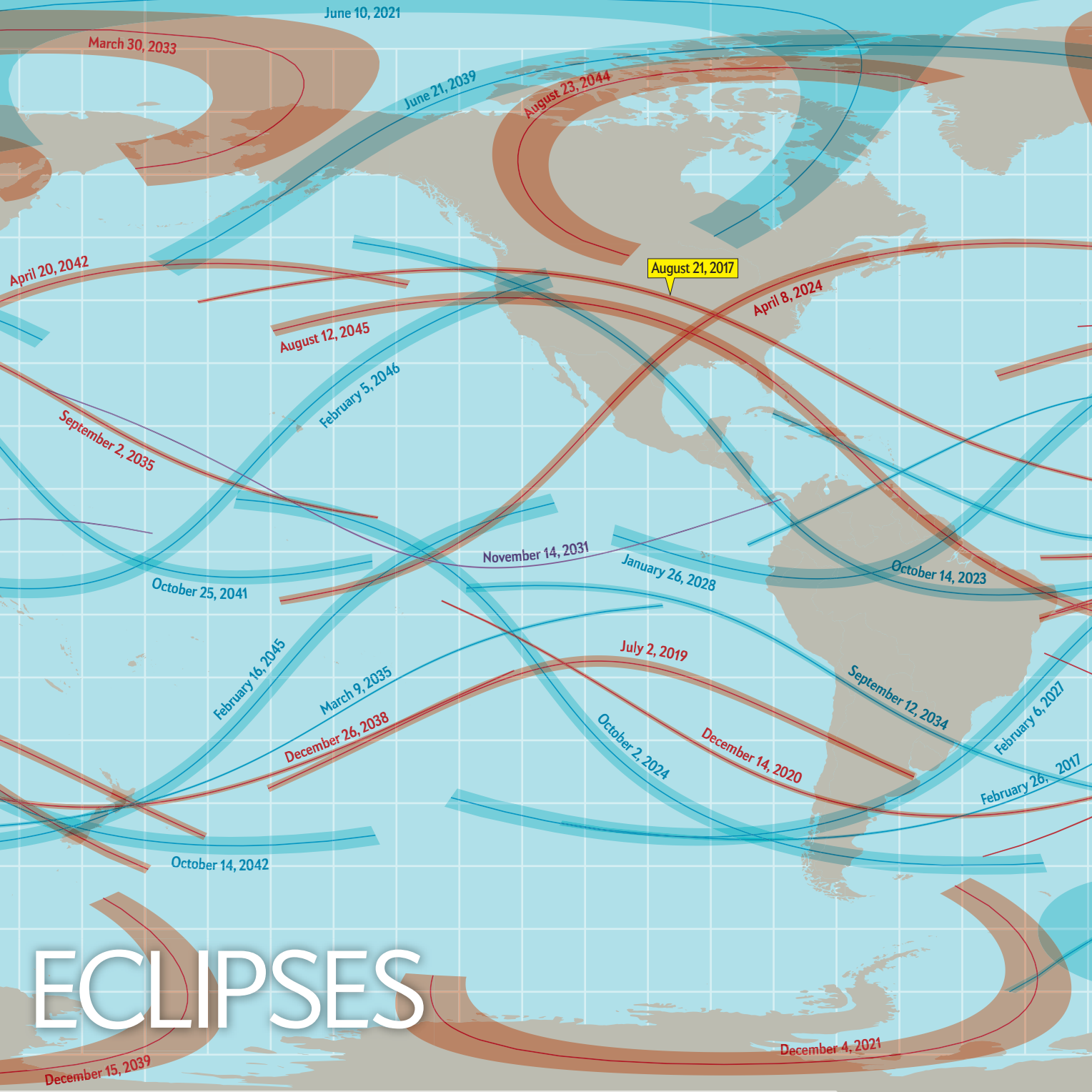
1,000 YEARS OF SOLAR

Opportunities abound to watch the sun disappear if you live long and travel

EXCITEMENT ABOUT THE AUGUST 21, 2017, ECLIPSE IS AS HOT AS A STAR, BUT SOLAR eclipses happen at least twice a year, when the orbits of the moon and Earth align with the sun. What is unusual this time is that the moon will totally block the sun, instead of doing so partially, and that the strip of darkness cast on Earth will fall on millions of people rather than plankton out at sea or polar bears or penguins at the poles. Forty-six solar eclipses of various types will occur over the next 30 years. Grab a friend and go. —*Mark Fischetti*

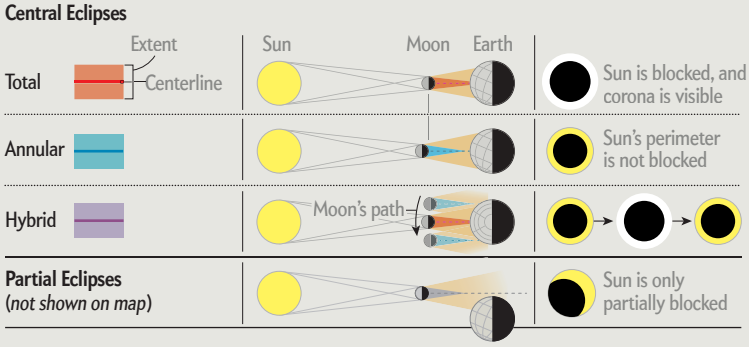
ECLIPSE PREDICTIONS BY FRED ESPENAK, NASA GSFC EMERITUS; CONSULTATION BY MICHAEL ZEILER

**The centerline of these odd eclipses just misses Earth, so only a small area sees darkness.*



ECLIPSES

Eclipse Tracks, 2017–2046



Several Ways to Hide the Sun

Central eclipses (*shown on map*) occur when the moon, as seen from Earth, passes fully in front of the sun. They come in three varieties. The eclipse is total when the moon is close enough to Earth to entirely block the sun. It is annular when the moon is farther from Earth and blocks only the middle of the sun. And it is hybrid when the distance to the moon varies during the event. A total eclipse creates a narrow band of complete darkness on Earth's surface; the closer the moon, the wider the band. (Flat maps exaggerate the width at the poles.) Observers on either side of the band will see dimmed sunlight, but that effect fades to nothing a few hundred miles away.

Graphic by Jan Willem Tulp (map) and Jen Christiansen (schematic)

Eclipses to the Year 3000

Creatures on Earth will witness 2,354 solar eclipses between 2017 and 3000. They will occur at regular intervals of slightly less than six months (*orbital diagram*), which means that each year, eclipse season shifts on the calendar (*big spiral*). Eclipses also occur in cycles; each successive eclipse in a cycle casts a similar shadow band on Earth (*map*). During a total eclipse, complete darkness at any given spot lasts less than seven minutes, so if you want to see one, plan ahead.

How to Read the Spiral

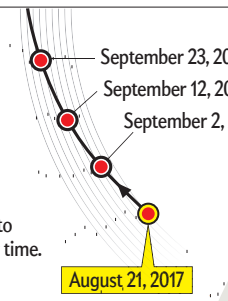
Each dot indicates a solar eclipse

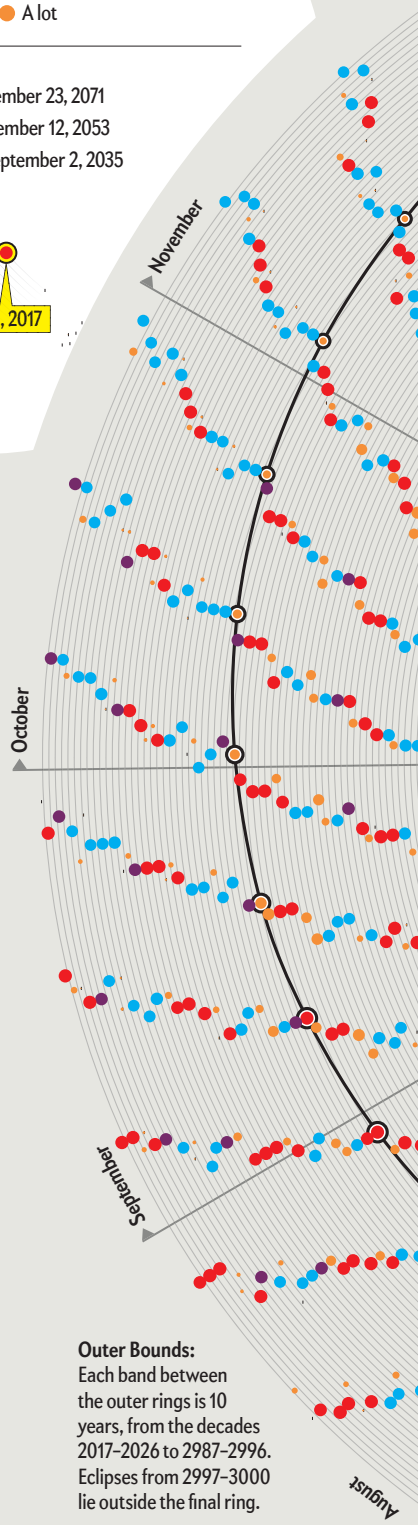
Total · Annular · Hybrid · Partial

Dot size of partial eclipses represents "magnitude"—the portion of the sun blocked by the moon

• A little · A lot

The August 21, 2017, eclipse belongs to the Saros 145 series. Each subsequent eclipse occurs about 18 years and 11 days later. The cycle, already in progress, will transition from central eclipses to partial eclipses over time.

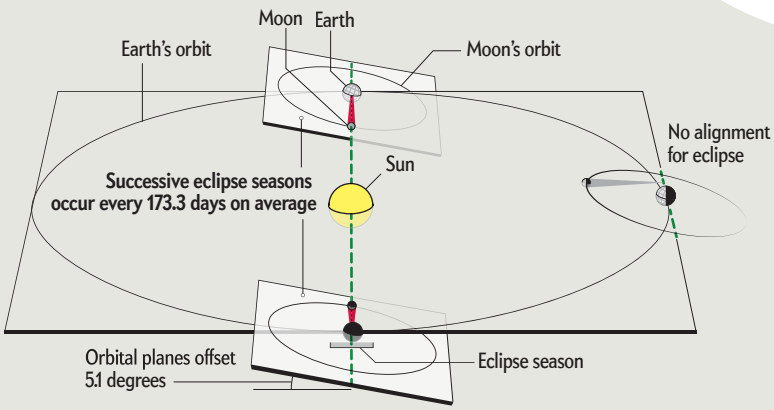




Outer Bounds: Each band between the outer rings is 10 years, from the decades 2017–2026 to 2987–2996. Eclipses from 2997–3000 lie outside the final ring.

Creating an Eclipse

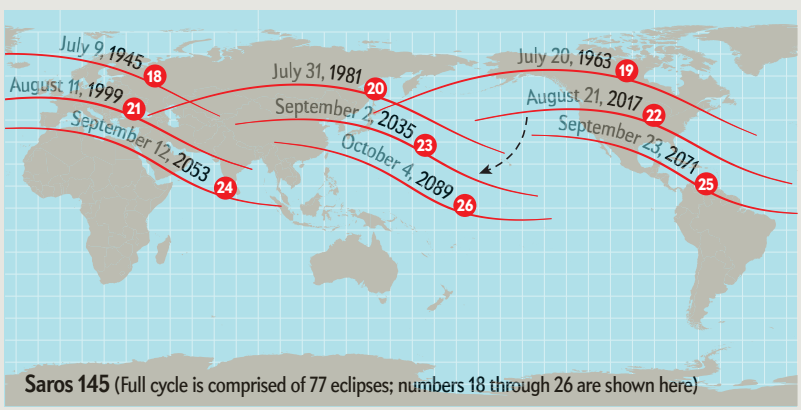
Solar eclipses occur when Earth, the moon and the sun line up on an axis. Because Earth and the moon both have elliptical orbits, and because the moon's orbit is inclined 5.1 degrees to Earth's, the alignment can take place only within a window of 34.5 days—the "eclipse season." Successive seasons occur every 173.3 days, meaning an eclipse happens every five to six months.



The Crazy Saros Cycle

Eclipses occur in cycles because the orbits of Earth and the moon follow a pattern, with respect to the sun, that aligns every 18 years and 11 and a third days*—an interval known as a Saros. Eclipses separated by one Saros create a similar path of darkness on Earth, but because of the extra third of a day, the path of each successive eclipse shifts about 120 degrees to the west. The August 21, 2017, eclipse belongs to the Saros 145 cycle. The next eclipse in that cycle, on September 2, 2035, will extend over Asia and the Pacific Ocean. Successive eclipses in the cycle will migrate southward until they pass Antarctica. Each Saros cycle lasts 1,225 to 1,550 years and creates 69 to 87 eclipses that migrate southward or northward. After that, the next eclipse path drifts beyond the south or north pole, missing Earth entirely, ending the cycle.

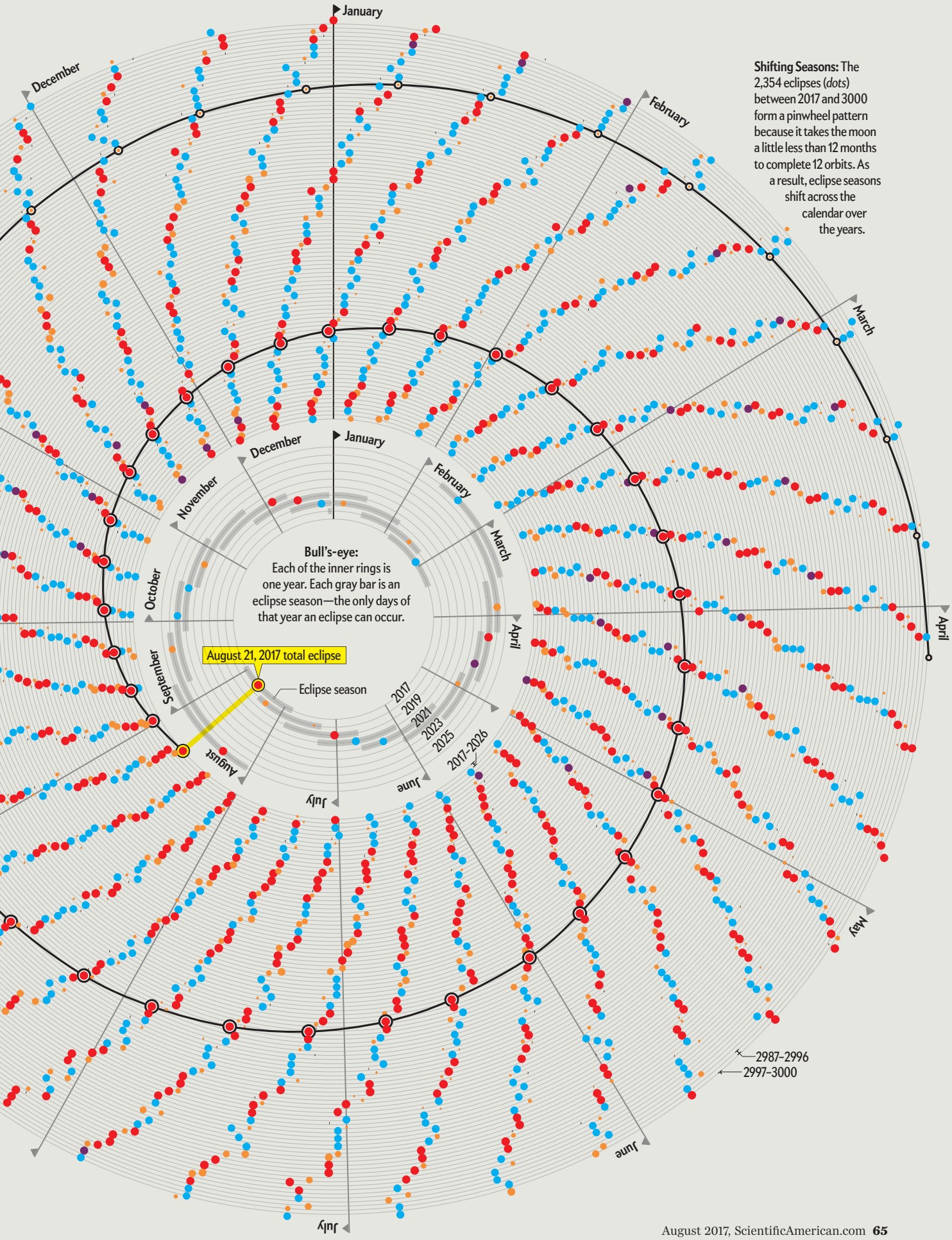
**The interval is sometimes 18 years and 10 and a third days, depending on leap years.*



Saros 145 (Full cycle is comprised of 77 eclipses; numbers 18 through 26 are shown here)

ECLIPSE PREDICTIONS BY FRED ESPENAK, NASA GSFC EMERITUS; CONSULTATION BY MICHAEL ZEILER

Graphic by Jan Willem Tulp (radial chart and map) and Jen Christiansen (orbital diagram)


January
February
March
April
May
June
July
August
September
October
November
December
Shifting Seasons: The 2,354 eclipses (dots) between 2017 and 3000 form a pinwheel pattern because it takes the moon a little less than 12 months to complete 12 orbits. As a result, eclipse seasons shift across the calendar over the years.
Bull's-eye: Each of the inner rings is one year. Each gray bar is an eclipse season—the only days of that year an eclipse can occur.
August 21, 2017 total eclipse
Eclipse season
2017
2019
2021
2023
2025
2017–2026
2987–2996
2997–3000

AGRICULTURE

BUILDING A BETTER HARVEST

Scientists are learning to manipulate the complex conversation that plants have with microbes, pests, nutrients and other elements of the phytobiome in hopes of averting a future famine

By Marla Broadfoot

Illustrations by Cherie Sinnen

Marla Broadfoot is a freelance science journalist and contributing editor at *American Scientist*. She is based in Wendell, N.C., and has a Ph.D. in genetics and molecular biology.

MERCEDES DIAZ TRAMPS INTO A muddy soybean field and runs her brightly manicured fingers through the limbs of dozens of knee-high plants. As she checks the stems, pods and leaves, she rattles off a list of possible maladies under her breath: pod borers, frogeye leaf spot, white mold. Diaz spots a tangle of mottled leaves and shouts, "SDS!"—signaling sudden death syndrome. She plucks one of the leaves and hands it to me. I turn the crinkly, palm-sized leaf over in my hand. Irregular holes riddle its surface, along with ugly brown spots tinged in yellow—the effects of a toxin produced by the SDS fungus that courses through the plant, robbing it of its pods and chewing up the leaves from the inside out. SDS is one of the top crop killers in the U.S. According to the United Soybean Board, it cost farmers more than 60 million bushels in lost yields in 2014. And yet Diaz could not be happier to see it in her field.

A plant pathologist, Diaz is one of a myriad of researchers hunting for new ways to protect crops from threats and to dramatically boost yields. In 2016 her team coated seeds with thousands of different microbes and planted them, along with control plots of untreated seeds, in half a million spots throughout the Midwest and South. Along the perimeter of these fields, the researchers deposited sentinel plots—sown with varieties susceptible to disease that act like the proverbial canary in the coal mine, warning of harms that might come to the rest of the crops. When Diaz finds SDS or some other blight in the sentinel plots and not in the test plots, it could be a sign that the microbes are working, helping to produce healthier, more abundant crops.

Yet on this rainy day last September, Diaz finds that both the test plots and the control plots have escaped the sentinels' fate. The microbes did not make a difference—or did they? Even an improved yield as high as six bushels per acre (over an average of about 50 bushels per acre for soy) is nearly impossible to spot on sight. She will have to wait for the plants to be harvested and the data to be analyzed to find out if any of the microbes helped.

Crop research tends to be a slow-paced, hit-or-miss business, but scientists such as Diaz feel they are racing against the clock. If agriculture does not change radically over the next few decades, there may not be enough food to go around. The world's population is projected to increase from 7.5 billion to 9.7 billion people by 2050. To feed those additional mouths—and accommodate changing diets that include more meat—farmers will need to increase food production by about 70 percent, according to the United Nations Food and Agriculture Organization (FAO). It is a tall order made taller by a number of worrisome trends. Global acreage of farmable land is shrinking as a result of urbanization and climate change, among other factors. Annual gains in yields for essential food crops have been plateauing, according to the FAO. Fertilizer use, for example, has reached a tipping point in which piling more chemicals onto fields will likely do more harm than good. Even genetically modified crops, at times both the devil and the darling of agriculture, have not lived up to their promise to supercharge food production.

"We need to stop looking for silver bullets," says Jan Leach, a plant pathologist at Colorado State University. "This is not a problem that any one of us can solve on our own, and it will require very diverse teams of people working together in ways that

IN BRIEF

To meet the global need for food, scientists are finding new ways to exploit the phytobiome—the complex web that links crops with microbial communities, soil, weather, animals and other environmental factors.

Among the most promising innovations are seeds coated with bacteria or fungi that can deter pests or otherwise promote growth. The first such products are already on the market.

Phytobiome-based interventions are likely to be less controversial than genetically modified seeds, but they do pose some potential risks. In any case, biotechnology alone cannot resolve world hunger.

we've never worked before." Leach and other scientists are championing a more holistic approach, one that takes into account how all the components on a farm—the plants, soils, microbes, insects and climate, known collectively as the phytobiome—interact to determine crop yields. The concept harks back to the writings of 19th-century naturalists Alfred Russel Wallace and Charles Darwin, who presented nature as a vast, interconnected web where species constantly adapt to the changing environment around them.

Take Diaz's beloved soybeans. When an insect lands on a soybean leaf, the plant might respond by secreting volatile chemicals through its roots, which, in turn, alter the microbial makeup of the soil. These microbes could then switch on an array of genes in neighboring plants, putting them on high alert for a potential attack. Such critical plant defenses are sensitive, however, to various environmental factors and could, for example, be vulnerable to climate change. Pathogens have their own amazing tricks. Some can shoot themselves off the surface of a leaf like a cannonball, catching a ride on air currents from field to field, continent to continent. From the clouds, some strains of high-flying microbes can even influence the weather, summoning rain and hail to return them to the earth.

Scientists have suspected this complexity for centuries, but only recently have advances in technology enabled them to map these intricate interactions in the hope of developing more systematic, sustainable solutions for agriculture. Using gene-sequencing tools, they can now measure all the microbes in the soil, even the rare varieties or persnickety strains that are impossible to grow in the laboratory. They can track how these microbial communities shift in space and time, perhaps as the result of a surge in fertilizer or a drop in temperature. They can record the conversations that microbes, plants and other organisms have with one another and try to decipher how that chemical communication drives crop productivity and health.

One day a farmer may be able to ride a specially equipped tractor into a field and take a comprehensive census of its microbial residents, along with the more typical measurements of "precision agriculture"—such as the soil's moisture levels and nutrient content. Those factors could then be combined with data on previous crop yields, potential pests and pathogens, and projected weather patterns to predict which combination of seeds, nutrients, chemicals and microbes should give the highest yield.

The movement to make this vision a reality has only just begun. Last year a diverse band of scientists released an ambitious plan for transforming the future of agriculture, *Phytobiomes: A Roadmap for Research and Translation*. With the *Roadmap* came the creation of the *Phytobiomes* journal, an academic publication, and the Phytobiomes Alliance, an industry-academic collaboration that includes more than a dozen entities—newbies such as BioConsortia and Indigo and familiar names such Diaz's employer, Monsanto. Over the past couple of years these companies have invested heavily to ramp up research and development, vying for their share of the global agricultural biologicals market, which is projected to reach $10 billion by 2020.

They see the ground below our feet—and its vast network of resident microorganisms—as vital to that effort. Soil-dwelling bacteria and fungi can help plants grow, cope with stress, bolster immune responses, and ward off pests and diseases. Farmers have known some of this since the late 1800s, when they began treating their pea and bean patches with the bacterium rhizobium, which adds nitrogen to the soil. Nowadays dozens of products based on the soil microbiome are on the market, with more on the way. Monsanto, in partnership with Denmark-based Novozymes, is betting big on microbe-laced seeds developed through the massive experiment that Diaz is part of. Other researchers are trying different tacks, such as altering the genome of crop plants in ways that would attract useful microbes or manipulating pest-plant communication so that crops can better detect and respond to a threat. Given the phytobiome's complexity, the possible avenues of influence are infinite. So are the dead ends. The challenge is to hit pay dirt in time to avert famine.

With the world's population projected to explode from 7.5 billion to 9.7 billion by 2050, farmers will need to increase food production by 70 percent.

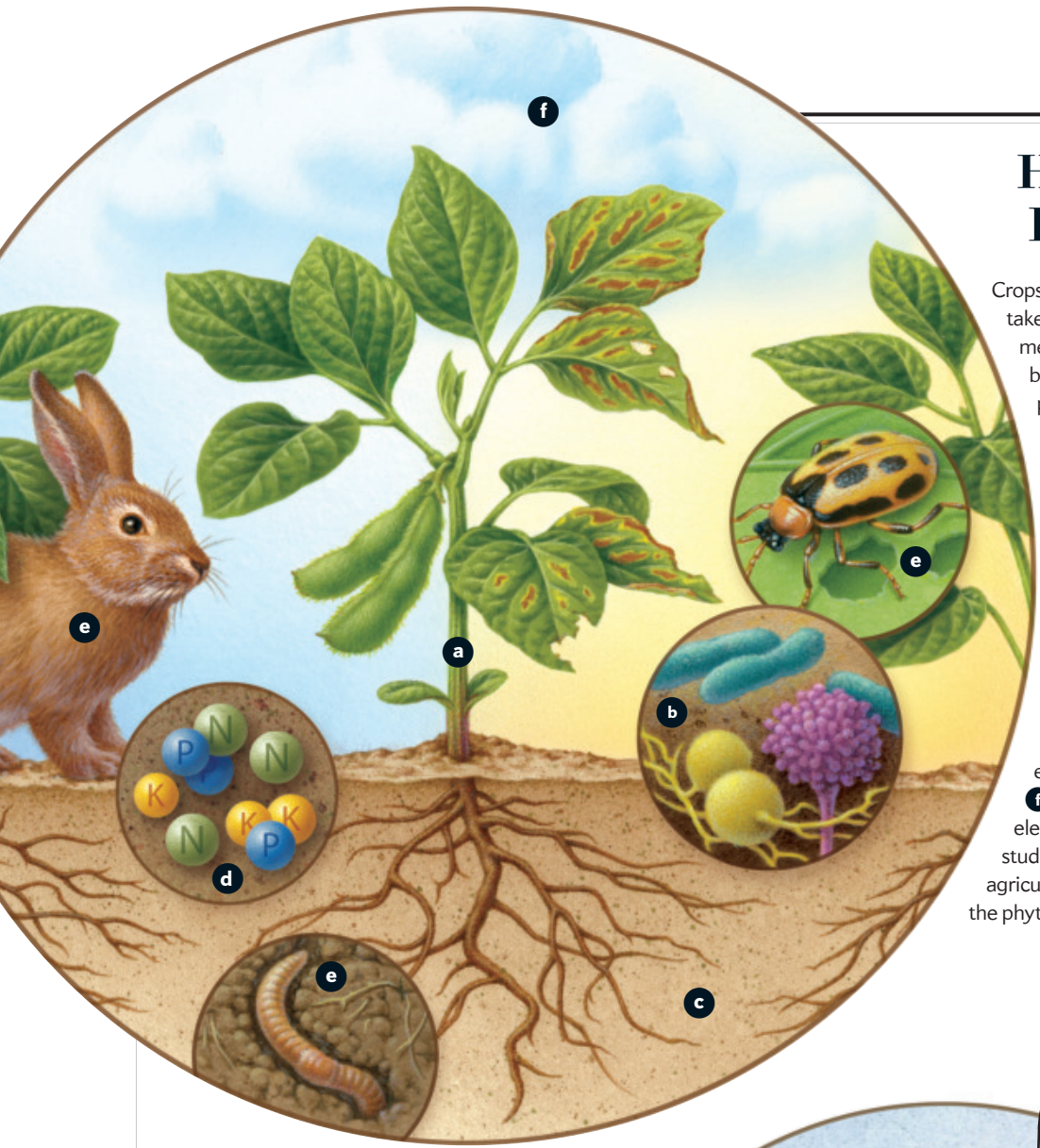
NOTES FROM UNDERGROUND

AN HOUR OUTSIDE OF ST. LOUIS, the cornfields look withered and pale in the mid-September sunlight. Stretches of soybeans resemble 1970s-style shag carpet dyed in shades of avocado green and harvest gold. I am traveling with Diaz and her colleagues to an unmarked site on the fringes of Stonington, Ill. As I step into a puddle, I grab my copy of the field map showing where thousands of microbe-laden seeds were sown. The microbes had been grown in vats of rich broth, coated on the seeds inside giant stainless steel bowls and then kept frozen until planting time. Once the seeds sprout, these microbes spring to life, but what happens next is shaped by the multiple factors that make up the phytobiome.

I enter a maze of cornstalks behind Diaz, who shows me several sentinel ears covered in pink mold, swarming with tiny whiteflies. Plants lack a bona fide immune system, but they have evolved a number of maneuvers to fend off insects. Some plants can thicken the walls of their cells so that intruders cannot get through, or they send toxic chemicals out to their roots or leaves to make them less palatable. Nicotine, caffeine and

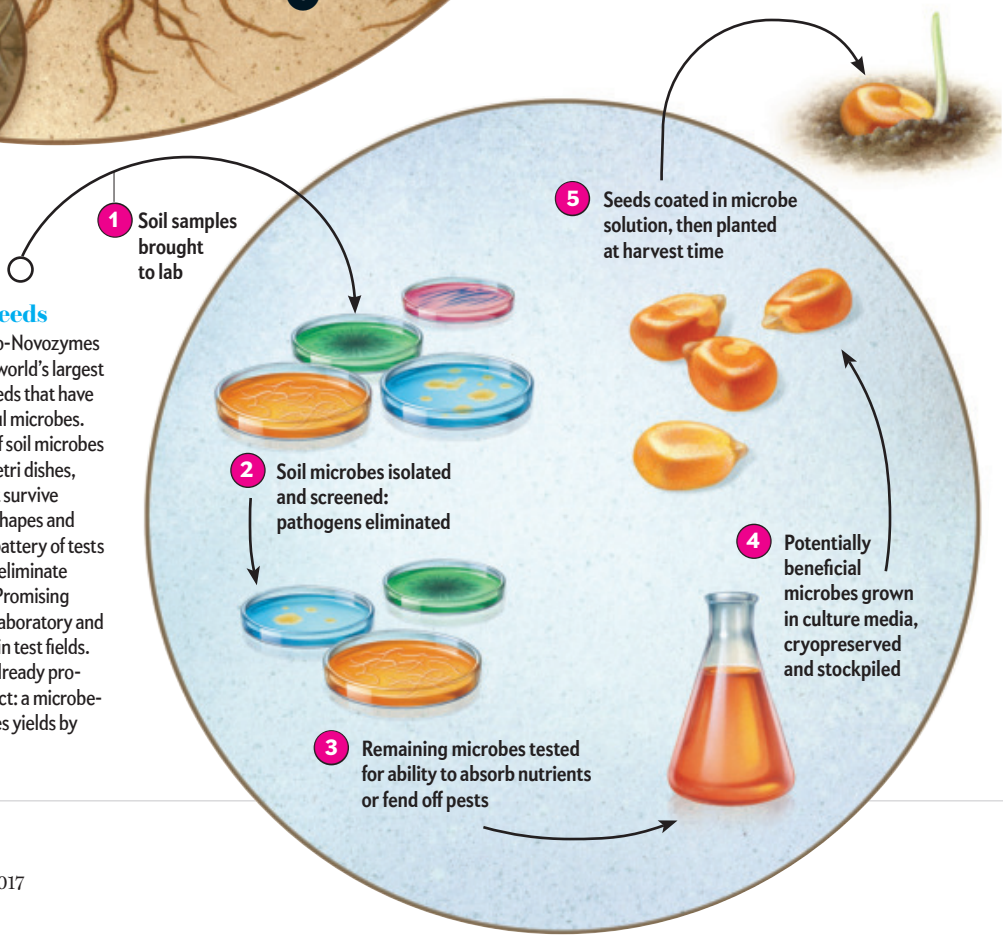
Hacking the Phytobiome

Crops (a) engage in a constant give-and-take with the living and inorganic elements of their environment, or phytobiome. This dialogue influences the plants' health. Bacteria, fungi and viruses (b) found on leaves, stems and roots and in the air and earth can provide a boost or a blight. The quality of soil (c) can alter how water, carbon and nutrients are cycled. Nutrients (d) such as nitrogen and phosphorus spur growth, but their overuse in chemical fertilizers degrades soil. Animals (e) such as rabbits and beetles are among the top crop destroyers, although others, such as earthworms, can be useful. Weather (f) and a changing climate impact all elements of this ecosystem. The case studies here demonstrate two ways that agricultural scientists are trying to shape the phytobiome to improve crop yields.



Case Study: Coated Seeds

The BioAg Alliance—a Monsanto-Novozymes partnership—is conducting the world's largest field-testing experiment with seeds that have been laced with potentially useful microbes. Its researchers harvest billions of soil microbes from U.S. farms; grow them in petri dishes, where the roughly 1 percent that survive produce colonies with dazzling shapes and colors; and run them through a battery of tests that include gene sequencing to eliminate those known to cause diseases. Promising microbes are then grown in the laboratory and coated onto seeds to be planted in test fields. The three-year-old project has already produced its first commercial product: a microbe-coated corn variety that increases yields by about three bushels per acre.



even the tannins that give red wine its astringent quality are all products of plant defenses.

Centuries of breeding and decades of genetic engineering have sought to enhance plant defenses and build other useful traits that increase crop yields. For example, more than half of the corn now grown in the U.S. contains a gene from an insect-killing bacterium called *Bacillus thuringiensis,* or Bt, that enables the corn to destroy beetle larvae. Now scientists are searching for other, phytobiome-related traits that could help promote plant health. They have discovered that plants spend as much as 30 percent of their energy trying to attract the right microbes and repel the wrong ones. Jeffery Dangl, a plant biologist at the University of North Carolina at Chapel Hill, is investigating ways to alter the plant genome to further cultivate this microbial entourage. He recently discovered a gene that shapes the communities of bacteria living in and around roots to soak up more phosphate—a nutrient in dwindling supply—from the soil.

Other phytobiome research focuses on resistance to bugs. Typically a plant can detect when pests are afoot by the presence of special chemicals called elicitors in the saliva of chewing insects. Gary Felton, an entomologist at Pennsylvania State University, and his colleagues discovered that some beetles and caterpillars can mask these telltale molecules by spitting up gut microbes onto the leaf, tricking the plant into reacting as if it were bathed in bacteria rather than ravaged by bugs. The misguided response to microbes actually disrupts the plant's ability to defend against insects. Recently Felton showed that feeding beetles a particular kind of bacteria skewed their microbiome enough so that they could no longer fool the plant [*see box at left*].

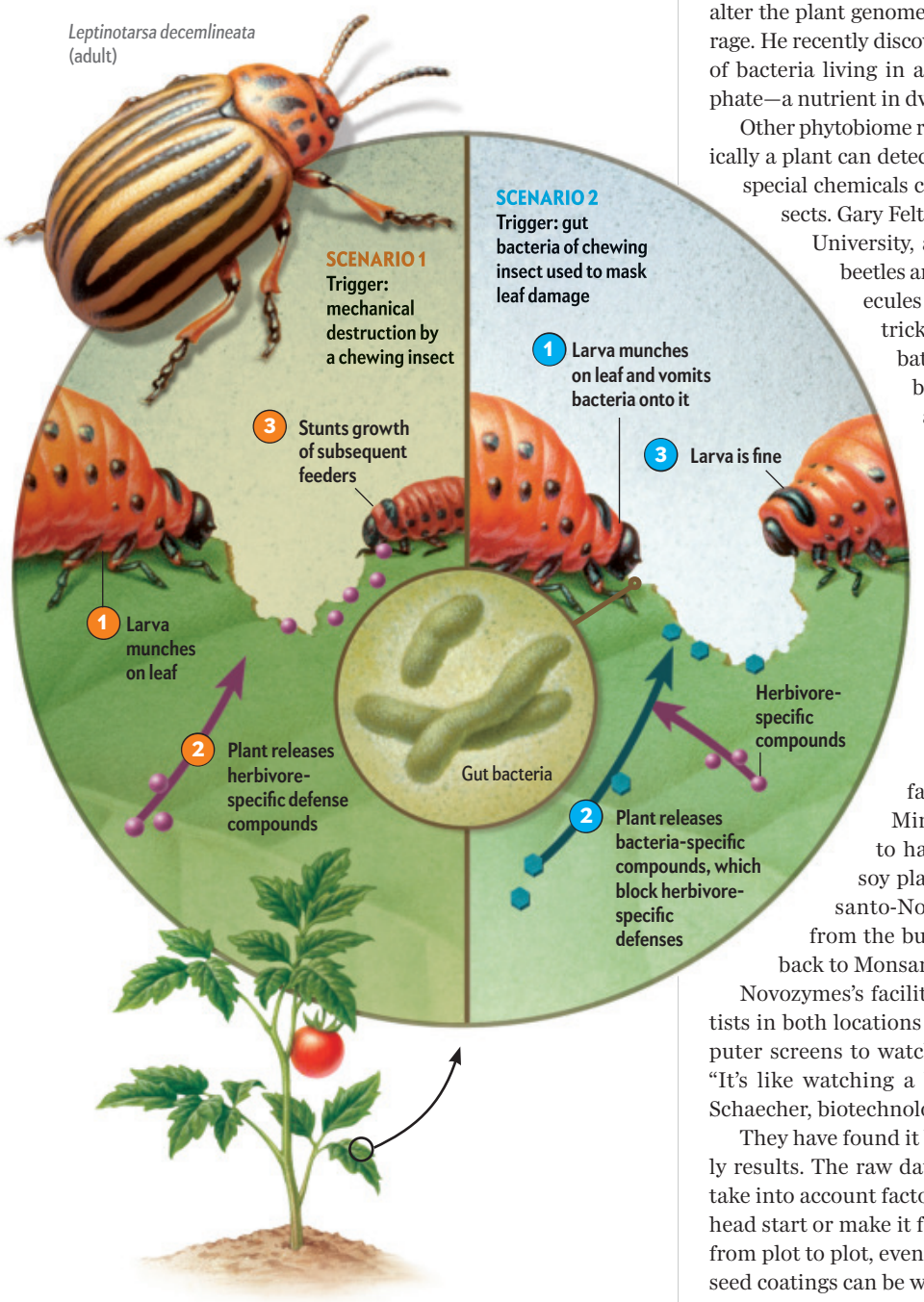
The next green revolution could spring from any or all of these methods of shaping the dialogue among plants, pests and soil dwellers. But first, there are experimental crops to tend and massive numbers to crunch.

Late last summer a fleet of machines fanned out into fields from Louisiana to Minnesota and North Carolina to Nebraska to harvest each of the test plots of corn and soy planted by the BioAg Alliance, as the Monsanto-Novozymes partnership is known. Data from the burly harvesters are streamed in real time back to Monsanto's data center in St. Louis, as well as to Novozymes's facility in Research Triangle Park, N.C. Scientists in both locations are known to hunker around their computer screens to watch the numbers come in from the fields. "It's like watching a horse race in slow motion," says Scott Schaecher, biotechnology data strategy lead at Monsanto.

They have found it best not to put too much stock in the early results. The raw data can be deceptive because they do not take into account factors that might give a particular microbe a head start or make it fall behind. The soil microbiome can vary from plot to plot, even across a field. Weather can wreak havoc: seed coatings can be washed off by early rains, and one year the alliance lost thousands of plots to Hurricane Joaquin. In addi-

Case Study: Microbe/Herbivore/Plant Interaction

Plants lack a formal immune system, but they can detect and respond to assaults by bugs and bacteria. An attack by chewing insects can trigger plants to release compounds that interfere with the insects' digestion and growth (*scenario 1*). A bacterial blitz provokes the release of different, antimicrobial compounds. Some insects, such as Colorado potato beetle larvae, can trick their host by regurgitating gut bacteria onto leaves, leading the plant to issue the wrong defense and leaving the insects unharmed (*scenario 2*). New research is exploring ways to unmask this deception.



Even if there were a broader sharing of data among crop scientists in private industry, academia and government, world hunger is not likely to be solved by biotech innovation alone. It will also take political will.

tion to half a million yield points, the team collects 50 different measurements on each of its soil samples. Add in other phytobiome data, and you end up with terabytes of information, what Schaecher calls either "a statistician's carnival or nightmare."

On his office computer, Schaecher pulls up a U.S. map decorated in red and green dots like a Christmas tree: green for the microbes that boosted yield, red for those that lowered it. They represent 2016 results from five corn fields. He and his team can break down the data according to soil and environmental characteristics, weather, and insect and disease pressure. They can zoom in on the locations with high levels of Diaz's SDS to see if they can identify any microbes that excelled under those conditions.

The team uses a "field first" strategy, which means it skips the typical greenhouse experiments and tests its candidates directly in the field. As a result, the researchers have no idea which, if any, microbes will give an advantage. In 2014, the first year of the field trial, they planted seeds coated with 500 different strains. Ninety percent of the microbes failed. In 2015 they put 2,000 microbes into the race, including the winners from the first year. After that trial, only a handful of the original contenders remained, along with a couple hundred of the newbies. In 2016 the scientists planted another 2,000 strains, made up of the top performers and a batch of new recruits. Three years into the experiment, only a single microbe from the initial round—plus hundreds from later rounds—remains in contention. The team is not looking for one-hit wonders—it wants Triple Crown winners that perform consistently, year after year, on multiple fields.

RISKY BUSINESS?

WORKING WITH ALL-NATURAL MICROBES—taken from farmland, grown in the lab and then returned to the farm—might seem like a harmless proposition, free of the kind of controversies associated with genetically modified organisms (GMOs). Nevertheless, it raises a number of concerns. Messing with the microbial milieu could affect the flavor of a crop, much as soil composition influences the taste of wine. A yield-boosting bacterium might possess pathogenic properties that prove harmful to human health. Long-term applications of plant probiotics could change the natural dynamics of soil, fueling the proliferation of some microorganisms while driving others to extinction. There is also a risk that seed coatings, like many agents applied to a field, could slough off one crop and contaminate another.

Schaecher says the BioAg Alliance works hard to avoid such problems. It puts its microbial strains through a battery of tests before introducing them into the field. It sequences each genome to make sure the microbe bears no resemblance to known human pathogens and runs other tests to assess if it might be toxic to the environment or spread to another crop. He and his team consult regularly with the U.S. Department of Agriculture, which decides whether a permit is required before a particular microbial species can undergo field-testing. Organisms with benign duties such as fixing nitrogen or solubilizing phosphate typically get a pass. Those with more dangerous jobs such as killing off other bacteria or fungi require more paperwork.

Among agricultural researchers, the bigger concern is not that newly introduced species will take over or spread to other crops but rather that they will not stick around long enough to do much of anything, says Gwyn Beattie, a plant pathologist at Iowa State University and one of the authors of the *Phytobiomes Roadmap*. A spoonful of soil contains about 50 billion microbes, a mix of up to 10,000 different species. Researchers can add millions of one strain to the soil and not make a dent. "If you throw one person [at a time] into New York City, the vast majority of people you throw in there do not change New York City," Beattie says. "It is like that in a microbial community. Introducing organisms rarely has an impact at all, and that's actually the biggest frustration." (A similar challenge has mired the human probiotics industry, which aims to enhance the multitrillion-member microbial community in the human gut. Its powders, pills and potables have been promoted for treating ailments ranging from diarrhea to depression, but few studies show any measurable effect.)

Still, Monsanto's activities have worried large segments of the public, which have accused the company of endangering human health, trampling the rights of farmers and monopolizing the food supply. Most of this ire arose in the mid-1990s, when the agricultural giant launched a line of GMO crops. Since then, two opposing narratives have emerged: one in which the company develops seeds that double yields and heroically overcome food shortages; the other in which its products defile farmlands and cause cancer. Last year the National Academy of Sciences completed what may be the most thorough examination of GMOs to date and found neither to be true. Its report concluded that genetically modified crops were just as safe to eat as conventional crops but that "there is no evidence" that GMOs have boosted progress on yields.

The primary benefit from genetically modified soybean, cotton and maize, the report suggested, was "favorable economic outcomes for producers who have adopted these crops." When I asked about the academy's lackluster findings, a Monsanto rep-

resentative admitted that the company had shifted its sales pitch from feeding the world to helping farmers get the best possible yields at the lowest cost. Monsanto's sales totaled $13.5 billion in 2016, nearly $10 billion of which came from seeds, many of them genetically enhanced. The advances of the past two decades have saved money for farmers and made money for industry, but the need for more food remains urgent.

TOMORROW'S HARVEST

THE SEEDS PLANTED on American farms today are not your grandfather's seeds. They typically carry as many as 14 different genetically engineered traits, piled on top of one another. These "stacks," as they are called in industry speak, are often accompanied by a host of other potentially yield-boosting products, including fertilizers, herbicides and, more recently, biologicals such as the BioAg Alliance's microbial seed coatings. Yet there is still a lot we do not know about what goes into a healthy crop—and scientists in academia and the government, as well as big agriculture, are all vying to figure it out.

Even with advances in sequencing technology, scientists have identified only 1 percent of the microbial species in soil. The murky nature of soil has made visualizing what is happening underground difficult. Scientists have had to resort to destructive end-point studies—shoveling up scoops of soil and taking a rough survey of its microbial constituents, like a giant running its hands across the earth to capture a sample of humankind. That approach might indicate which people are there but not what they were doing or how they were interacting before their world was turned upside down.

A few years ago a team in Scotland concocted a see-through artificial soil that allows researchers to spy on the microbial communities associated with plant roots. Elizabeth Shank, a microbiologist at Chapel Hill, has been using this transparent soil to study the microbes' signals. These chemical messages range from lethal—70 percent of antibiotics are derived from metabolites microbes use to off one another—to productive—some microbes use them to announce they are gathering to form a biofilm so that they can stick onto the surface of roots. Last November, Shank presented her work at a symposium on phytobiomes in Santa Fe, N.M. She explained that by painting different microbial metabolites with fluorescent markers, she can watch messages travel between communities as they react to events such as the planting of a seed, a rise in temperatures or an invasion by pathogens.

Her innovation may yield big payoffs. Or not. Many academics such as Shank are licensing their discoveries to businesses or launching their own start-ups. The commercial ecosystem is thrumming with new entities, collaborations and mergers, including last September's $66-billion purchase of Monsanto by Bayer. The U.S. government has also gotten into the game. The 2014 "farm bill" allotted $200 million to establish the Foundation for Food and Agriculture Research (FFAR) to encourage academic-industry partnerships. In July 2016 FFAR convened a group of experts to brainstorm about how to reap the most benefits from the phytobiome.

Kellye Eversole, executive director of the Phytobiomes Alliance, says that although academia, government and industry might share similar goals, their methods are sometimes at odds. Because companies are beholden to their investors, they can have a short-term, profit-driven mentality. "Not having fundamental research and building that long-term pipeline can hurt us," she says. On the other hand, industry has resources the botany professors can only dream of: A few days after the FFAR event, Monsanto's Schaecher made a presentation at the American Phytopathological Society meeting, a yearly powwow of more than 1,500 plant pathologists. When he pulled up the map of the BioAg Alliance's field trials, Linda Kinkel, a plant pathologist at the University of Minnesota, nearly fell out of her chair. "If they're truly collecting data on 500,000 soil microbiomes, that's more than all the rest of us put together." And she worries, "How much science is in there that we'll never see?"

Leveraging the phytobiome to improve crops will require a thorough integration of information from different sources and disciplines, but many of the parties involved are not forthcoming. Farmers are hesitant to give others access to the data they gather in their fields, citing privacy concerns. The BioAg Alliance occasionally feeds bits and pieces to academic collaborators, but Schaecher says it cannot share all its data because Monsanto and Novozymes have to "protect their competitive advantage." This year the alliance launched its first product, a microbial seed coating based on a fungus found in cornfield soil that increased yields by an average of three bushels per acre in field tests. Projections suggest the product could be used to boost crop yields on up to 90 million acres of farmland globally.

It is a start but a long way from meeting the needs of an increasingly burdened planet. Even if there were a broader sharing of data among crop scientists, world hunger will not likely be solved through biotech innovation alone. That entails addressing not only the food supply but also food waste, distribution challenges, war, political strife, income inequality and climate change. Fred Gould, an entomologist at North Carolina State University, who led the National Academy of Sciences review of GMOs, cautions that even if scientists could somehow double food production, it might not be the right thing to do if it leaves the soil ravaged and unable to support future crops. He also warns that solutions have to work on the ground. "You can have all of this knowledge, but it is so environment-dependent, you are going to have to manipulate [the phytobiome] for each farm," Gould says. "When the rubber meets the road, some of these ideas are hard to put into practice." In the end, hacking the phytobiome will likely be just part of the next agricultural revolution. It will also take political will and a lot of luck. After all, 2050 is a mere 32 annual cropping cycles away. SA

MORE TO EXPLORE

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PSYCHOLOGY

TALKING TO OURSELVES

Studies of the conversations people have with themselves open a window on the hidden workings of the mind

By Charles Fernyhough

Illustration by Daniel Stolle

Charles Fernyhough is a professor of psychology at Durham University in England. His research focuses on child development, memory and hallucinations. He writes fiction and nonfiction. Fernyhough's latest book—*The Voices Within* (Basic Books, 2016)—is on self-talk.

MY ALARM WOKE ME EARLY. I WAS IN A HOTEL ROOM IN LONDON, NEAR THE headquarters of the BBC. I hadn't slept well. When I looked in the bathroom mirror, I saw someone pale and slightly terrified. I had reason to feel nervous. In just over an hour I would be speaking live to an audience of millions on the BBC's flagship radio discussion program, *Start the Week*. As I gazed into the mirror, I was aware that I was talking, silently, in my head. My words were a reassurance. They were aimed at me. "Relax," I said. "You've been on *Start the Week* before." I had the impression that I was speaking to myself but was also hearing something internally, the familiar shadow of a voice.

This is a story about everyday experience: the thoughts, images and sensations that go through your head as you are soaking in the tub, chopping onions in the kitchen or waiting for the door to open on an important meeting. When asked, people often say that their inner lives contain a lot of words. Psychologists use the term "inner speech" for this phenomenon, in which people talk to themselves silently in their head. It has a cousin, "private speech," in which people talk to themselves audibly. If you say words to yourself, such as "Remember to get some coffee" or "Stick to the plan," without making a sound, then you are using inner speech. If you say something similar to yourself out loud, it is private speech.

Both forms of language seem to have varied purposes, including planning and monitoring our behavior, regulating our emotions and fostering creativity. Among adults, inner speech seems to be more common than the private variety and, of particular interest to psychologists, is thus the form that probably plays the biggest part in our thinking. It is also quite a bit more difficult to study. When I was starting out in research in the 1990s, there was hardly any scientific literature on the topic. That situation has changed dramatically over the past couple of decades, partly because researchers have developed new experimental techniques for studying inner speech and partly because we now have a richer notion of how it functions, what forms it takes, and how it can benefit and hinder a thinker. In fact, we are starting to realize that inner speech elucidates some big questions about the mind and brain.

A CHAT WITH ONESELF

HENRY IS LYING on a play mat with a toy train in each hand, rhapsodizing about the make-believe city he is about to create. "First the cars. Then a *big* train," he says to himself. Henry is three years old. Walk into any nursery or preschool, anywhere in the world, and you will see (and hear) something similar. It can get noisy, with a classroom of kids thinking to themselves out loud. But this natural phenomenon of children's private speech provides some important clues about where the words in our head come from.

Scholars have long pondered the private speech of young children. In the 1920s Swiss developmental psychologist Jean Piaget proposed that this type of self-talk reflected the inability of youngsters to take other people's perspectives and adapt their speech to their listeners. In this view, private speech was the result of a failure to communicate with others. That was why

IN BRIEF

Most people talk to themselves in their head, a phenomenon psychologists call inner speech.

This self-talk helps us plan, regulate our emotions and be creative, among other important functions. But it has eluded study.

In recent years psychologists have made significant inroads into analyzing inner speech, partly because of studies that use medical-imaging technologies to observe the brain at work.

Their findings reveal some of the neural bases of these private conversations and cast light on some long-standing mysteries of the mind.

it was thought to drop away as children got older, and they became more skilled at taking the perspectives of their listeners into account.

In the 1930s a Russian psychologist named Lev Semyonovich Vygotsky proposed an alternative explanation for private speech: children deliberately repurpose words that they have previously used successfully in social interactions with other individuals. Instead of regulating the behavior of others, they were getting the hang of using language to control themselves. Research in the intervening decades has bolstered Vygotsky's theory of how inner speech develops and how it comes to have the functions it has.

Discovering Vygotsky's writings as a student in developmental psychology, I remember being struck by the simplicity of his idea. It felt as though the theory of how verbal thought develops should be more complicated. But although his notion was itself straightforward, its ramifications were quite complex. Vygotsky was suggesting that the silent self-talk people engage in as adults is an internalized version of the conversations we have with others when we are developing as children. Nearly a century after Vygotsky wrote down his insights, I and other inner speech researchers are only beginning to unpack what they mean for understanding how words function in our thinking.

One of the most important implications of Vygotsky's theory is that inner speech should have the same structure as out-loud conversation: namely the quality of a dialogue between different points of view. This concept of thinking as mental dialogue is not new—it traces back at least as far as the philosopher Plato—but I latched onto its potential to reframe some deep mysteries of human cognition. One such mystery is about control: How it is that an intelligent system can come up with, and implement, new ideas about how to act? A robot can get very smart at responding to what happens in the environment, but what makes it come up with the idea of doing anything for itself? If the system has to be told what to do, then it is lacking one of the essences of intelligence.

What excited me about dialogue is that it is, by its very nature, self-regulating. When you are in conversation with another person, there is no third party standing there waving a conductor's baton to show you where the conversation should go next. You and your conversational partner regulate each other through the normal processes of questioning, challenging, responding, agreeing, and so on. Understanding self-talk in these terms seemed to hold out the prospect of explaining how human thought can be open-ended—not always directed toward a particular goal—and inherently flexible.

To do dialogue, though, you need to be able to represent something of the point of view of the person with whom you are in conversation. (It was the failure of just this kind of perspective taking that Piaget thought explained young children's private speech.) You often do not know in advance what the other person is thinking, but once you figure it out, you need to be able to keep it in mind and update that representation of his or her point of view as the conversation unfolds. Scientists now know a fair bit about the neural basis for such perspective taking, thanks in part to studies carried out using functional MRI and other medical imaging techniques that can reveal which brain regions carry out a given task.

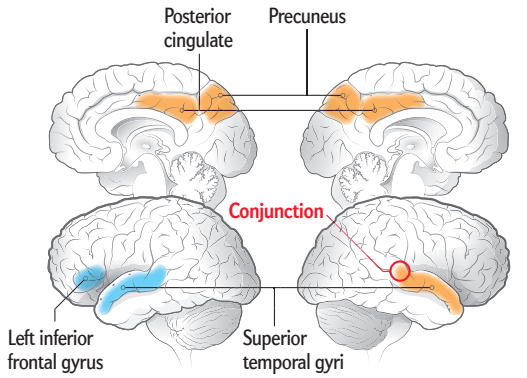
Armed with these insights, my collaborators and I have been testing a new idea about how mental dialogues happen, based on the suspicion that they recruit the same parts of the brain used in perspective taking. In an fMRI experiment led by my colleague Ben Alderson-Day of Durham University in England, participants produced two forms of inner speech while lying in a brain scanner. We asked our volunteers to generate some inner speech that had a monologic structure; in other words, it did not involve a conversational exchange between different points of view. We

Origins of Inner Speech

Medical imaging of the brains of people engaged in self-talk reveals fascinating differences in the neural underpinnings of inner dialogues compared with those of monologues. The interpretation of such neuroimaging studies requires caution, however, because study designs can influence results: the brain regions activated during spontaneously generated inner speech diverge from those that are activated when inner speech is produced on demand.

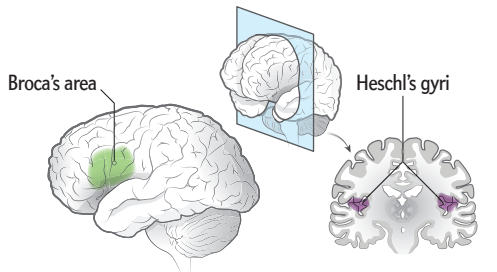
Monologue vs. Dialogue

Functional MRI studies indicate that monologic inner speech recruits the standard language system that is activated during any kind of speech (*blue*). Dialogic inner speech, for its part, additionally uses a number of other neural regions (*orange*). Intriguingly, the brain areas that appear to be involved specifically in internal dialogue overlap with a region that has been linked to thinking about other minds (*red*).



Rote vs. Spontaneous

In another fMRI study, participants who were asked to say particular words to themselves showed activations in Broca's area, part of the brain's standard language system (*green*). Spontaneous inner speech, in contrast, activated regions farther back in the temporal lobes (*purple*).



SOURCES: "THE BRAIN'S CONVERSATION WITH ITSELF: NEURAL SUBSTRATES OF DIALOGIC INNER SPEECH," BY BEN ALDERSON-DAY ET AL., IN *SOCIAL COGNITIVE AND AFFECTIVE NEUROSCIENCE*, VOL. 11, NO. 1; JANUARY 2016 (*monologue vs. dialogue*); "EXPLORING THE ECOLOGICAL VALIDITY OF THINKING ON DEMAND: NEURAL CORRELATES OF ELICITED VS. SPONTANEOUSLY OCCURRING INNER SPEECH," BY RUSSELL T. HURLBURT ET AL., IN *PLOS ONE*, VOL. 11, NO. 2, ARTICLE NO. E0147932; FEBRUARY 4, 2016 (*rote vs. spontaneous*)

Illustration by Tami Tolpa

also asked participants to conduct an inner dialogue. In each case, we presented a particular scenario as the theme for the inner speech, such as a visit to one's old school. For the monologue condition, participants might be giving a speech to some students; in the dialogue, chatting to their former principal.

We predicted that both kinds of inner speech would recruit the standard language systems that activate when people are asked to produce any kind of speech: specifically, areas at the boundary between the brain's left frontal and temporal lobes and an area farther back in the part of the brain known as the superior temporal gyrus. We thought that inner dialogue would be special, however, in additionally activating parts of the brain known to be involved in thinking about other minds. These brain regions underpin our so-called social cognition system, which functions to help us represent other people's thoughts, beliefs and desires.

The new science of inner speech tells us that it is anything but a solitary process. Much of the power of self-talk comes from the way it orchestrates a dialogue between different points of view.

The results supported our predictions. When people were doing inner dialogue, their language system seemed to be working in conjunction with a part of their social cognition system, located in the right hemisphere close to the junction between the temporal and parietal lobes. Subjects did not exhibit this pattern of brain activity when they generated silent monologues. Although these findings need to be replicated, they provide preliminary evidence for a collaboration, spanning the two brain hemispheres, between two systems that are usually understood to have different functions. This neural linkage of language and social cognition seems to support Vygotsky's intuitions that when people are talking to themselves, they are having an actual conversation.

CAUGHT IN THE ACT

THERE ARE LOTS OF REASONS to be cautious in interpreting neuroimaging findings and, in this case, for overturning what had previously been understood about the neuroscience of inner speech. Most previous studies had simply asked participants to repeat sentences to themselves silently in their head in a monologic, nonconversational manner—the kind of inner speech you might do as you wander around a supermarket trying to remember the last few items on your list. It is supremely useful when the moment demands it but a long way from the creative and flexible inner dialogues that stem from treating ourselves as participants in a social exchange. Our research team put the conversational properties of inner speech front and center, but we were still asking our volunteers to do something quite unnatural: to talk to themselves on demand rather than waiting for inner speech to bubble up naturally. The problem is that cognitive neuroscientists need to be able to control things to understand what an experiment's findings really mean. Hanging around for inner speech to happen naturally seems to run against the idea of a rigorous experimental method.

What we need are ways of capturing inner speech as it occurs. Recently our team has taken a step in that direction by using a sophisticated method for garnering descriptions of people's inner experience known as descriptive experience sampling (DES). In this method, participants are trained to report on moments of inner experience when cued by a beeper. The process prompts the subjects to focus on whatever they are thinking, feeling, hearing, and so forth at the moment just before the beep went off and to take brief notes on those experiences as they occur. The following day the volunteers are interviewed in great depth about each moment of experience captured by the beep so that researchers can describe whether it was characterized by inner speech, sensory awareness or any of several other common phenomena.

My colleagues and I conducted the first ever study to couple this powerful method with fMRI. In it, we ran the conventional inner speech experiment, asking people to say particular words to themselves silently as they lay in the scanner. We also used DES to capture moments of experience as they happened naturally. We picked out those beeps in which we were fairly sure inner speech had occurred, based on the DES interviews, and compared the brain activations with those we had obtained in the standard task.

The differences were striking. Whereas the standard "rote repetition" method activated Broca's area (a part of the brain that is often implicated in the production of internal and external speech), spontaneous inner speech gave more pronounced activations farther back in the temporal lobe, in Heschl's gyrus. In terms of patterns of brain activation, naturally occurring inner speech contrasted dramatically with the kind that is produced on demand.

These findings have broad implications for how we go about investigating inner experience in cognitive neuroscience. They raise hard questions about how investigators approach the study of inner speech and what we can assume about *any* kind of mental experience we might think can be generated on demand. They underscore the need for what I like to call slow neuroscience: harnessing the power of neuroscientific techniques to very careful descriptions of human experience.

There are other reasons for taking care to describe inner speech in all its varieties. In Vygotsky's theory, dialogue and monologue are not the only variables of internal self-talk. A big feature of his scenario is the idea that, as language is internalized to form private and then inner speech, its form changes. Vygotsky saw several ways in which this might happen, including different kinds of abbreviation or condensation. In my anxious thoughts in my London hotel room, I caught myself saying a full sentence to

myself: "You've been on *Start the Week* before." At other times, the language I direct at myself is much more stripped down. If I hear a shrill beeping sound from the kitchen when I'm cooking, I might say to myself something such as "The oven timer is going off." It is more likely, though, that I will simply say, "The timer." Vygotsky noted that inner and private speech are often abbreviated, relative to utterances directed at another person. In self-talk, we usually do not have to put things into full sentences, in part because the utterance is for the self, and we therefore do not have to spell out all the details. The great Russian-American novelist Vladimir Nabokov recognized how our thoughts can have a compressed form relative to what we might say out loud. "We think not in words but in shadows of words," he wrote in his notes for *Pale Fire,* according to a 1964 interview.

Oddly enough, no one had examined this feature of internal language until recently. Simon McCarthy-Jones, now at Trinity College Dublin in Ireland, and I put together an online questionnaire asking people about different qualities of inner speech. Our team has also used a smartphone app to gather such data as people go about their daily lives. The results of our initial study, published in 2011, reveal four main qualities of inner speech: its dialogical nature, its tendency to be condensed, the extent to which it can incorporate other people's voices, and its role in evaluating or motivating our behavior. Only a minority of people indicated that their inner speech tends to be condensed, but this quality is common enough to warrant further investigation.

Above all, this questionnaire-based research confirms the view that inner speech is not just one thing. It appears to come in different forms that may be adapted to different functions and that will quite possibly have different neural underpinnings. A challenge for the future is to try to understand whether the brain handles condensed inner speech differently from its expanded form. That will require either a way of eliciting condensed inner speech experimentally in the brain scanner or further developments in capturing it as it occurs naturally. Inner speech remains an elusive target of study.

A KEY TO CREATIVITY

THE STUDY OF INNER SPEECH has taken great strides since I started pondering it as a graduate student in the 1990s. A facet of mental life that was generally considered impenetrable to science has yielded to new experimental methods and neuroscientific techniques. And as it happens, this intimate aspect of consciousness can illuminate some important questions about the human mind.

For a start, inner speech can provide some clues about the origin of human creativity. Once people have the architecture for internal conversations, we can use it in all sorts of ways, from arguing with ourselves to conversing with an entity that is not there. Because we have internalized dialogues with others, we retain an "open slot" for the perspectives of other beings: whether or not they are present, are still alive or ever even existed. My dialogues with God, a deceased parent or an imaginary friend can be as richly creative as those I have with myself. Asking ourselves questions and then answering them may be a crucial bit of apparatus for taking our thoughts into new territories.

Another routine experience with links to self-talk is one of the most familiar and private of them all. The moment you open a book, your inner speech is hijacked in all kinds of interesting ways. Neuroscientists have shown that reading a fictional character's speech activates the same parts of the brain we use to process other people's voices. Using an online survey, our team recently asked a large sample of keen readers about the "voices" they heard when they were reading fiction. Around one in seven of our respondents said that the voices of fictional characters spoke as vividly in their mind as if there had been another person in the room uttering the words.

Some of our participants gave us more detail on their experience of fictional voices. Using the tools employed in literary scholarship to analyze narrative, we examined their open-ended descriptions for more clues to literature's power to colonize our thoughts. For at least some of our respondents, the voices of fictional characters continued to resonate even after the book had been put down. A few even adopted the personas of fictional characters as they went about their daily lives—looking out through the eyes of Mrs. Dalloway (the character from Virginia Woolf's novel of the same name) during a routine visit to Starbucks, for example. Marco Bernini of Durham University calls this phenomenon "experiential crossing." These findings give us important clues about how our mind might represent the voices and characters of the social beings with whom we share our world.

The new science of inner speech tells us that it is anything but a solitary process. Much of the power of self-talk comes from the way it orchestrates a dialogue between different points of view. Like the collaboration my colleagues and I saw between the language system of the left hemisphere and the social cognition networks of the right, the inner speech network must be able to "plug in" to other neural systems as the situation demands—when we have verbal thoughts about the past and future, when we use words to talk ourselves through demanding tasks or when our mind simply wanders, with no particular objective in mind. If researchers get the science right, verbal thought stands to elucidate all these features of our cognition.

It may be because it is such an ordinary thing that inner speech has received so little scientific attention. But the next time you find yourself psyching yourself up for a challenge, talking yourself through a dilemma, ticking yourself off after a mistake or just planning your evening in a cozy out-loud mumble, you might want to think about the private, intimate wonder of your self-directed use of words. In everyday life, as in the lab, the voices of inner speech have much to tell us. SA

MORE TO EXPLORE

The Varieties of Inner Speech: Links between Quality of Inner Speech and Psychopathological Variables in a Sample of Young Adults. Simon McCarthy-Jones and Charles Fernyhough in *Consciousness and Cognition,* Vol. 20, No. 4, pages 1586–1593; December 2011.

Inner Experience in the Scanner: Can High Fidelity Apprehensions of Inner Experience Be Integrated with fMRI? Simone Kühn et al. in *Frontiers in Psychology,* Vol. 5, Article No. 1393; December 9, 2014.

The Brain's Conversation with Itself: Neural Substrates of Dialogic Inner Speech. Ben Alderson-Day et al. in *Social Cognitive and Affective Neuroscience,* Vol. 11, No. 1, pages 110–120; January 2016.

Uncharted Features and Dynamics of Reading: Voices, Characters, and Crossing of Experiences. Ben Alderson-Day et al. in *Consciousness and Cognition,* Vol. 49, pages 98–109; March 2017.

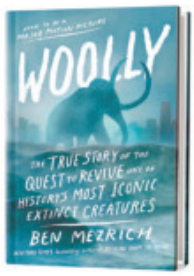
FROM OUR ARCHIVES

Why Children Talk to Themselves. Laura E. Berk; November 1994.

By Andrea Gawrylewski

Woolly: The True Story of the Quest to Revive One of History's Most Iconic Extinct Creatures

by Ben Mezrich. Atria, 2017 ($26)



TOOTH of an extinct woolly mammoth, from the Natural History Museum in London.

What if extinction weren't permanent after all? Several years ago pioneering Harvard University geneticist George M. Church (who serves on *Scientific American*'s advisory board) and his colleagues launched a project to resurrect the famous woolly mammoth by splicing its preserved genetic code with that of an elephant. Animals like the mammoths, which adapted to live in steppe habitats, prevent tree growth and turn and stomp topsoil, exposing the earth underneath to the cold winds of the region, thereby lowering the ground temperature and preserving the underlying permafrost (and the potent greenhouse gas methane locked within it). Thus, a reestablished population of woolly mammoths might be a heavyweight stopgap to methane-driven climate change. As much a profile of Church and his rise to renowned scientist as it is a tour of the latest research on climate change, species extinction and conservation biology, author Mezrich's telling is riveting and almost too like fiction to be believed.

Through the Shadowlands: A Science Writer's Odyssey into an Illness Science Doesn't Understand

by Julie Rehmeyer. Rodale, 2017 ($25.99)

At the height of her illness, Rehmeyer would wake up unable to move her arms or legs or sometimes even to speak. The many doctors she saw offered no treatment but diagnosed her with chronic fatigue syndrome (CFS)—a poorly understood and hardly studied affliction. Desperate, the science writer reluctantly turned to other CFS patients on the Internet who touted a theory she initially dismissed as crazy—that toxic mold was making her sick. Their recommendation: trash most of her belongings and spend two weeks in the desert to escape the mold. She tried it and was shocked to find herself on a path to rapid recovery. In this engrossing memoir, Rehmeyer describes her frustration at a medical system that has failed CFS patients and her conflicting emotions around the improbable but effective remedy she found. —*Clara Moskowitz*

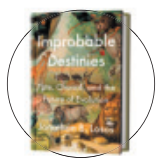
Quakeland: On the Road to America's Next Devastating Earthquake

by Kathryn Miles. Dutton, 2017 ($28)

In 1959 an earthquake near Yellowstone National Park killed 28 people, most of whom were camping along Hebgen Lake when a collapsing canyon wall buried the area in a landslide of 80 million tons of boulders and trees. The force of the falling rock created a hurricane-strength wind that overturned cars and ripped survivors from their campsites. Science journalist Miles uses the Hebgen Lake earthquake as an example of the damage these events can wreak. She spent a year exploring the U.S.—sometimes climbing far below the earth's surface—with scientists who study seismic activity. She discusses the mechanics of quakes, the increase in human-induced tremors, the ways cities are safeguarding infrastructures (or not) against damage, and advances in technology that make these fleeting but powerful phenomena easier to predict. —*Andrea Marks*

Improbable Destinies: Fate, Chance, and the Future of Evolution

by Jonathan B. Losos. Riverhead, 2017 ($28)



When evolutionary biologists observe that some traits in nature evolve independently over and over again (hydrodynamic body shape in large ocean animals like dolphins and sharks or spiny protrusions in unrelated porcupinelike mammals from Africa or North America), they wonder whether such traits are inevitable. Is evolution predictable, always yielding the same traits, or is it contingent on infinite variables, delivering infinite outcomes? Evolutionary biologist Losos profiles the latest probes into this question, including his own work in the Bahamas monitoring lizard body measurements in various habitats. He concludes that evolution is somewhat predictable, though only to a certain extent. Plenty of random chance led the planet's evolution down one path and not another. Have the earth's species been lucky in this regard? "Yes," he answers. "Destined? No."

MARY EVANS *age fotostock*

Michael Shermer is publisher of *Skeptic* magazine (www.skeptic.com) and a Presidential Fellow at Chapman University. His next book is *Heavens on Earth*. Follow him on Twitter @michaelshermer

Are We All Racists?

Private thoughts and public acts

By Michael Shermer

Novelists often offer deep insights into the human psyche that take psychologists years to test. In his 1864 *Notes from Underground,* for example, Russian novelist Fyodor Dostoyevsky observed: "Every man has reminiscences which he would not tell to everyone, but only to his friends. He has other matters in his mind which he would not reveal even to his friends, but only to himself, and that in secret. But there are other things which a man is afraid to tell even to himself, and every decent man has a number of such things stored away in his mind."

Intuitively, the observation rings true, but is it true experimentally? Twenty years ago social psychologists Anthony Greenwald, Mahzarin Banaji and Brian Nosek developed an instrument called the Implicit Association Test (IAT) that, they claimed, can read the innermost thoughts that you are afraid to tell even yourself. And those thoughts appear to be dark and prejudiced: we favor white over black, young over old, thin over fat, straight over gay, able over disabled, and more.

I took the test myself, as can you (Google "Project Implicit"). The race task first asks you to separate black and white faces into one of two categories: White people and Black people. Simple. Next you are asked to sort a list of words (joy, terrible, love, agony, peace, horrible, wonderful, nasty, and so on) into either Good or Bad buckets. Easy. Then the words and the black and white faces appear on the screen one at a time for you to sort into either *Black people/Good* or *White people/Bad*. The word "joy," for example, would go into the first category, whereas a white face would go into the second category. This sorting becomes noticeably slower. Finally, you are tasked with sorting the words and faces into the categories *White people/Good* or *Black people/Bad*. Distressingly, I was much quicker to associate words like joy, love and pleasure with *White people/Good* than I was with *Black people/Good*.

The test's assessment of me was not heartening: "Your data suggest a strong automatic preference for White people over Black people. Your result is described as 'automatic preference for Black people over White people' if you were faster responding when *Black people* and *Good* are assigned to the same response key than when *White people* and *Good* were classified with the same key. Your score is described as an 'automatic preference for White people over Black people' if the opposite occurred."

Does this mean I'm a closeted racist? And because most people, including African-Americans, score similarly to me on the IAT, does this mean we are all racists? The Project Implicit Web site suggests it does: "Implicit biases can predict behavior. If we want to treat people in a way that reflects our values, then it is critical to be mindful of hidden biases that may influence our actions."

I'm skeptical. First, unconscious states of mind are notoriously difficult to discern and require subtle experimental protocols to elicit. Second, associations between words and categories may simply be measuring familiar cultural or linguistic affiliations—associating "blue" and "sky" faster than "blue" and "doughnuts" does not mean I unconsciously harbor a pastry prejudice. Third, negative words have more emotional salience than positive words, so the IAT may be tapping into the negativity bias instead of prejudice. Fourth, IAT researchers have been unable to produce any interventions that can reduce the alleged prejudicial associations. A preprint of a 2016 meta-analysis by psychologist Patrick Forscher and his colleagues, made available on the Open Science Framework, examined 426 studies of 72,063 subjects and "found little evidence that changes in implicit bias mediate changes in explicit bias or behavior." Fifth, the IAT does not predict prejudicial behavior. A 2013 meta-analysis by psychologist Frederick Oswald and his associates in the *Journal of Personality and Social Psychology* concluded that "the IAT provides little insight into who will discriminate against whom."

For centuries the arc of the moral universe has been bending toward justice as a result of changing people's *explicit* behaviors and beliefs, not on the basis of ferreting out *implicit* prejudicial witches through the spectral evidence of unconscious associations. Although bias and prejudice still exist, they are not remotely as bad as a mere half a century ago, much less half a millennium ago. We ought to acknowledge such progress and put our energies into figuring out what we have been doing right—and do more of it. SA

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Illustration by Izhar Cohen

Steve Mirsky has been writing the Anti Gravity column since a typical tectonic plate was about 36 inches from its current location. He also hosts the *Scientific American* podcast Science Talk.

What's the Deal?

Man with bizarre views being investigated by authorities

By Steve Mirsky

Person of interest is an overweight man of approximately 70 years of age with orange hair who was reported to be repeatedly riding up and down the escalators in a gaudy midtown Manhattan skyscraper. When approached by local authorities, subject claimed to be a prominent billionaire, the host of a wildly successful television game show and the president of the United States. Given the grandiose nature of these claims, subject was detained for observation.

During a rambling interview, subject decried the presence of "haters and losers" who were out to get him, contrasting this with his own perceived status as "a winner," which he credited to a possibly unique genetic makeup. To wit: "I have great genes and all that stuff, which I'm a believer in"; "God helped me by giving me a certain brain"; "I have like a very, very high aptitude"; "Maybe it's just something you have. You know, you have the winning gene."

When questioned about his unusual hair configuration, subject replied in a somewhat long-winded fashion with various statements, such as "You know you're not allowed to use hair spray anymore because it affects the ozone … 'cause you know hair spray's not like it used to be, it used to be real good…. If I take hair spray, and I spray it in my apartment, which is all sealed, you're telling me that affects the ozone layer?"

Subject further claimed to be in possession of a Twitter account followed by tens of millions of people, all of whom recognize his greatness. He said he has used Twitter to explain, among other things, that climate change is a fiction. Examples of his beliefs on this topic include:

"Give me clean, beautiful and healthy air—not the same old climate change (global warming) bullshit! I am tired of hearing this nonsense"; "The concept of global warming was created by and for the Chinese in order to make U.S. manufacturing non-competitive"; "Well, I think the climate change is just a very, very expensive form of tax…. And I often joke that this is done for the benefit of China. Obviously, I joke. But this is done for the benefit of China, because China does not do anything to help climate change." When challenged on these statements, subject responded: "I did not. I did not. I do not say that" but also said he abandoned the Paris climate accord to stop other countries from "laughing at us."

Subject also contended that vaccinations can cause autism and has tweeted the following messages:

"Healthy young child goes to doctor, gets pumped with massive shot of many vaccines, doesn't feel good and changes—AUTISM. Many such cases!" and "I am being proven right about massive vaccinations—the doctors lied. Save our children & their future." Subject furthermore claimed to have been the sole authority invited to discuss autism on an episode of *Fox & Friends,* despite his complete lack of medical or scientific training or any expertise on the topic.

In what appears to be a related delusion that expertise is actually a liability when it comes to assessments of scientific validity, subject claimed that, as president of the United States, he submitted a budget to Congress that would cut funding to the National Institutes of Health by 18 percent; the Food and Drug Administration by 31 percent; the National Science Foundation by 11 percent; the Environmental Protection Agency by 31 percent; and the Centers for Disease Control and Prevention by 17 percent.

When asked why he was riding the escalator, subject expressed his personal "theory" about exercise: "All my friends who work out all the time, they're going for knee replacements, hip replacements—they're a disaster" and reportedly compared the human body to a battery with a finite amount of energy, which would be depleted by exercise.

Subject requested a steak (well done) and a cola drink. He awaits further special counsel from Dr. Mueller. SA

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Illustration by Matt Collins

1967 Efficient Agriculture

"The fact that the production of food and fiber engages only 5 percent of the U.S. labor force is primarily due to the mechanization of farming. Other technological developments—chemical fertilizers, pesticides, plant breeding and so on—make essential contributions, but mechanization is still the outstanding factor. The picking and winnowing of a crop usually accounts for at least half of the total cost of production. It is also by far the most difficult part of the agricultural process to mechanize. Nevertheless, the mechanization of harvesting in the U.S. has made such strides that, in spite of the costliness of the machines and other technical aids, the cost of food to American families, in terms of its percentage (18 percent) of their income, is the lowest in the world."

Department of Agriculture figures from 2015 show the proportion of family food spending in the U.S. was still the lowest.

Does the Ocean Floor Spread?

"The hypothesis that the floor of the oceans has been spreading seeks to explain some characteristics of ocean basins and the continents by supposing that material welling up from the interior of the earth forms mid-ocean ridges and then, as new material rises, moves outward, away from the ridges. The hypothesis has been strengthened recently by the discovery that bands of alternating normal and reversed magnetism parallel the mid-ocean ridges, apparently indicating upwellings of molten rock during different magnetic 'polarity epochs.'"

1917 Protecting Wildflowers

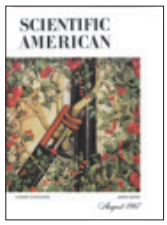
"For the past fifteen years a few Nature-lovers have been carrying on in this country an earnest campaign on behalf of the preservation of our native wildflowers and other wild plants. According to a review of these efforts published by Mrs. Elizabeth Britton in the *American Museum Journal,* some of the plants that stand in most urgent need of protection are now nearly extinct in many parts of the country where they were once common. The preservation movement began in 1901 with a fund of $3,000 to be used for 'investigation and preservation of our native plants.' The Wild Flower Preservation Society of America now has chapters in several cities. The fund secures essays, leaflets, posters and lantern-slides for illustrated lectures in schools and colleges."

Britton had also helped establish the New York Botanical Garden in 1891.

Cable Car for Freight

"The expeditious handling and quick-unloading of freight cars today is a most important factor in industrial war mobilization, particularly in handling iron ore at the docks. A new type of car pusher for the purpose of speeding up the unloading of cargoes and cars and eliminating the necessity of a switch engine is shown in the illustration. The pusher is propelled by a single cable, which runs between the rails the full length of the dock. The cable is securely anchored to concrete foundations at both ends through a spring tension device, which keeps it taut."

Industrial freight handling, 1917: using cable cars at the docks.



1967

1917

1867

1867 Teaching Dentistry

"Forty years ago surgeons and doctors generally officiated as teeth-pullers whenever occasion demanded. In 1820 there were but 30 practicing dentists in the United States. In 1850 the number had increased to 2,923, and at present there are about 5,000. A college for the education of those desiring to enter this profession has been established over a year in this city [now the N.Y.U. College of Dentistry], and the faculty of Harvard College, at their last Commencement, provided for a department of dentistry."

A Disgrace to Civic Pride

"Without an exception, the New York markets are a disgrace to the city and discreditable to the enterprise of our people. It is surprising that such dirty, inconvenient, and disgraceful shams as our markets, are not supplanted by structures which would be creditable to American enterprise. Buildings might be erected in place of the tumble-down shanties now dignified with the name of markets, which would be not only objects of pride as architectural structures, but be made sources of revenue. Few public improvements are more needed in New York City than market-houses, which are at the present, literally a stench in the nostrils of the people."

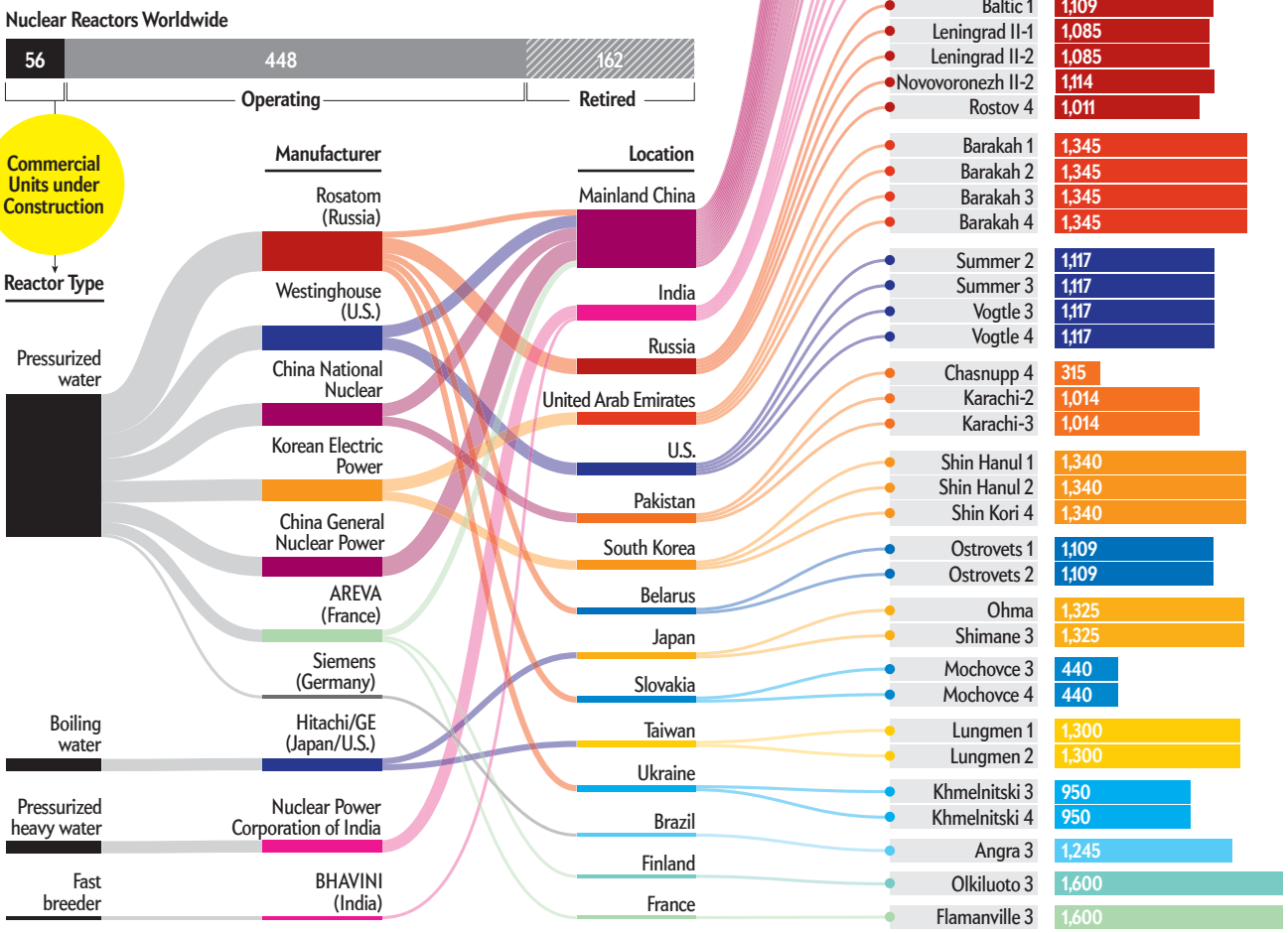
SCIENTIFIC AMERICAN, VOL. CXVII, NO. 7, AUGUST 18, 1917

Reactors Reshuffled

Asia aggressively builds nuclear power plants as the West withdraws

Nuclear power is hot in China. The country is building 19 commercial reactors, including two of the largest ever assembled. Russia's state-owned engineering firm, Rosatom, is erecting 13 reactors in five countries. India is developing its own domestic supply chain. Meanwhile the U.S. is canceling reactors, leaving only four under construction. American maker Westinghouse, long the global front-runner, filed for bankruptcy in March. France, which for decades happily relied on atomic power, will turn to renewables to meet new electricity demand. Germany will shutter all its reactors by 2022.

If China's progress holds, it will have more nuclear capacity than the U.S., today's leader, within a decade. The government helps companies get permits and obtain financing, two big hurdles in the West. Changing markets could shift alliances as well, as countries such as the United Arab Emirates sign deals with surging Russian and South Korean suppliers rather than fading American and European firms. Japan may be Asia's anomaly: because of the infamous Fukushima accident, it has scaled back plans. *—Mark Fischetti*



SOURCE: WORLD NUCLEAR ASSOCIATION

Graphic by Jen Christiansen